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SEISMIC PERFORMANCE OF BASE ISOLATED BUILDINGS AT DIFFERENT STAGES OF CONSTRUCTION

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Abstract

Seismic isolation is one of the most effective vibration control techniques in current earthquake engineering practice. Its main function is to mitigate the damage in structures exposed to strong ground motions, through both the increment of the fundamental period of vibration and the adequate addition of damping, which lead to diminish floor accelerations and drift ratios. Currently, this technology is applied in many earthquake-prone zones in the world, including leading countries like United States, Japan and New Zealand, and others in which its use has started more recently, which is the case of Peru.

Given the seismic hazard which threatens countries located in regions of high tectonic activity, particularly in developing countries, it is possible that a severe seismic movement may occur when a projected isolated building is under construction. Usually, the analysis and design of base isolated structures do not take into account their dynamic behavior at different stages of construction. Although an isolated structure under construction tends to have a greater isolation ratio, it has lesser mass and consequently higher isolation effective stiffness which conduct to shorter periods and greater associated damping ratios. These may result in reduced efficiency of the isolators.

Aware of that fact, the authors herein studied the seismic performance of the Information Center Building of the School of Civil Engineering at the National University of Engineering, in Lima, at several construction stages. The structure was designed to withstand optimally the displacements and forces due to earthquakes when its eight stories are completed. However, the construction will be carried out in two stages, and only the first four stories will be completed in the near future. Several nonlinear time history and response spectrum analyses of the isolated building were carried out, considering the two stages of construction previously mentioned in addition to a stage in which only the first story on the base isolation system exists. These numerous analyses were performed using maximum considered earthquake (MCE_R) ground motions. The results obtained were assessed, contrasted and discussed in this paper.

The conclusions were then extrapolated to other base isolated buildings on the basis of the analysis of the uniform linear shear beam on a linear isolator model. Detailed and easy-to-use graphics are here presented to estimate seismic responses quickly, which include the augmentation of the higher mode contributions because of isolation system damping. That increase is considerable when such damping is greater than twenty percent.

Keywords: base isolation; construction stages; shear beam model; higher mode contributions

1. Introduction

Preliminary estimations of the fundamental period, the isolation ratio and the base shear force of an isolated building at different stages of construction in the event of an earthquake are pertinent. Indeed, Fig.1 shows two isolated shear beam models [1] which represent the finished and partially constructed building respectively.

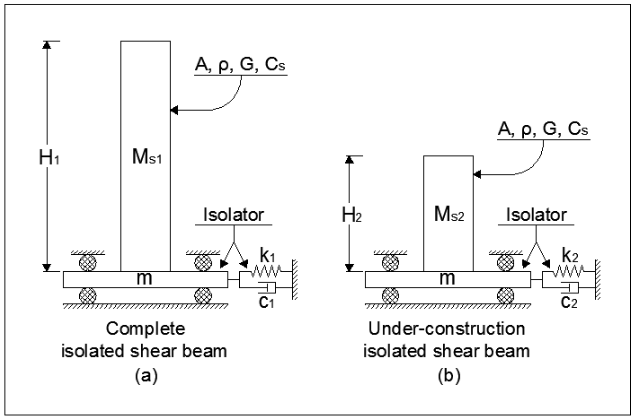

Fig. 1 – Shear beams on linear isolators

Where:

- A = Shear beam cross-sectional area
- H_i = Shear beam height
- ρ = Material density
- G = Material shear modulus
- C_s = Shear wave velocity
- m = Isolation system mass
- k_i = Isolation system effective stiffness
- c_i = Isolation system damping coefficient

The fixed-base fundamental period of the shear beam model in Fig.1a is:

$$T_{f1} = \frac{4H_1}{C_s} \tag{1}$$

And the effective period of the respective isolated shear beam is:

$$T_{01} = 2\pi\sqrt{\frac{M_1}{k_1}} \tag{2}$$

Being M_1 the total mass of the system; i.e.:

$$M_1 = m + M_{S1} = m + \rho A H_1 \tag{3}$$

The isolation ratio of the first shear beam is defined as:

$$r_1 = \frac{T_{01}}{T_{f1}} \tag{4}$$

If $H_2=H_1/2$, then $M_2>M_1/2$. Now, considering the force-displacement curve of isolators as hysteretic, the maximum displacement of the shear beam model at the isolation level in Fig.1b is lower than the corresponding displacement in Fig.1a; therefore, $k_2>k_1$. Thus:

$$T_{02} \approx \frac{T_{01}}{\sqrt{2}} \tag{5}$$

$$r_2 \approx \sqrt{2} r_1 \approx 1.4 r_1 \tag{6}$$

Where T_{02} and r_2 are the effective period and the isolation ratio of the shear beam of Fig.1b, respectively.

According to Eq. (2), (3) and (5) and applying an equivalent lateral force procedure, the relationship between base shear forces V_{b1} and V_{b2} is approximately:

$$V_{b2} \approx \frac{\sqrt{2}}{2} V_{b1} \approx 0.7 V_{b1} \tag{7}$$

Then, even though M_2 is near $0.5M_1$, it doesn't mean that the base shear force will be reduced at the same ratio.

Moreover, from Eq. (6), it could be concluded that the under-construction shear beam is better isolated than the complete shear beam. However, the lesser the isolation system maximum displacement is, the greater the isolation system damping ξ is. Having more damping in the isolation system increases the structural response in the higher modes, which may result in the increment of floor accelerations, story drifts ratios and story shear forces. This apparently contradictory phenomena happens because higher modes in a base isolated structure are almost orthogonal to the base shear [2]. Precisely, Fig. 2 includes two general graphics which show that the contribution of the second mode to the first-story shear force V_{st2} augments if r and ξ increase, reaching values even greater than the first mode contribution V_{st1}, particularly when T_f rises (tall buildings).

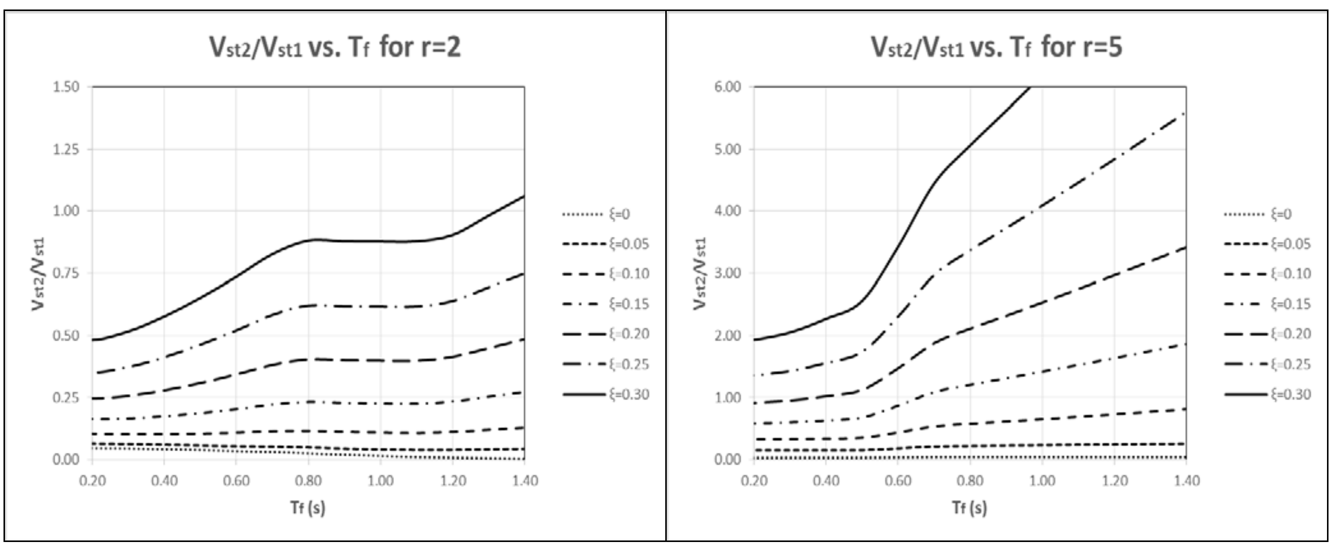

Fig. 2 – Increment of the second mode shear force at first story V_{st2} as a function of T_f, r, ξ and V_{st1}

Given that the isolated shear beam model is composed by one undamped part (shear beam) and one damped component (isolator), non-classical modes appear as ξ augments [3]. Response spectrum analysis was applied to graph these curves, being the results based on the moduli of the complex response.

From the results shown in Fig. 2, it would be possible to have a first-story shear V_{st} in the partially constructed building even greater than the one expected in the complete structure. This possibility was considered in the design of the new Information Center Building of the School of Civil Engineering at the National University of Engineering, in Lima.

2. Dynamic analysis of the Information Center Building

2.1. Description of the isolated building

The Information Center Building is a reinforced concrete structure which has a regular configuration and a moment-resisting-frame structural system. The area of the base level is 574m^2 and the projected number of stories is eight, having a total height of 28.80m, but only the first four floors will be completed in the near future. At its final stage, the seismic weight of the construction will be 4858 tonf approximately. The isolation system is composed by twenty similar lead rubber isolators (LRB) that are placed on rigid soil (see Fig.3).

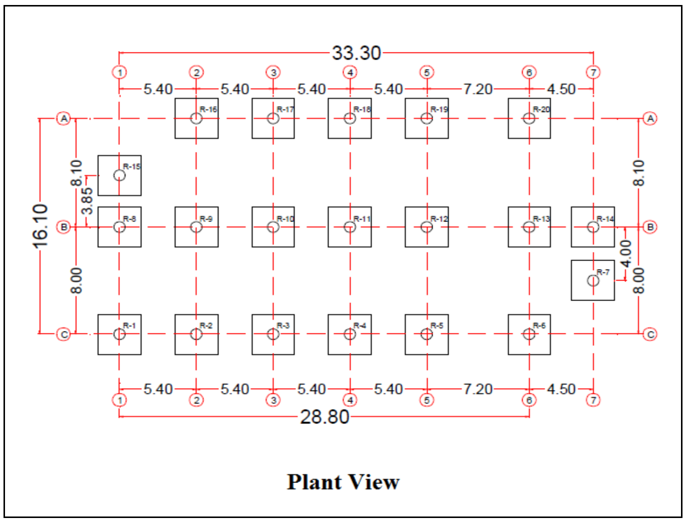

Fig. 3 – Plant of the Information Center Building

The hysteretic behavior of this kind of isolators is modeled through a bilinear curve [4], as shown in Fig. 4.

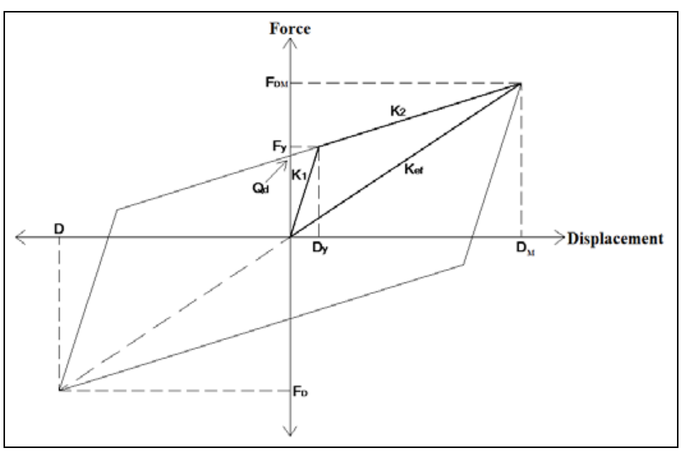

Fig. 4 – Force-displacement curve of isolators LRB at D_M

In this case, the primary stiffness K_1 is nearly ten times the secondary stiffness K_2, whose value is 1020 tonf/m. The characteristic strength Q_d is 6.55tonf, which represents the 90% of the yielding force F_y. Finally, D_y, the displacement at F_y, is 0.0071m and D_M, the maximum displacement, is 0.30m [5].

2.2. CISMID's artificial seismic records

There are no available natural earthquake records of events having magnitudes consistent with the expected MCE_R level in Peru, as required for time history analysis of an isolated building. It motivated that Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation, CISMID, upon request of SENCICO, selected several strong natural Peruvian, Japanese and Chilean seismic events and then, applying the spectral matching technique, developed 189 sets of artificial seismic records (3 components per set) in 2013. Twenty one of them had response spectra very close to the established design spectrum for rigid soils [6] located on the most seismically active zone in Peru.

For this work, 7 sets of these artificial accelerograms were chosen – only including horizontal components - based on their time duration and frequency content: 1985_Chile_Valparaiso, 2001_Arequipa_Moquegua, 2001_Geiko_Hiroshima, 2005_Tarapaca_Pica, 2007_Pisco_PCN, 2010_Maule_Curico and Simulation_PQR_5_1. The 14 records were scaled by a factor of 1.5 in order to perform the time history analysis at MCE_R level [7] (see Fig.5).

One additional reason for using only artificial seismic records is that smoother response spectra permit fairer comparisons among responses from time history and response spectrum analysis methods.

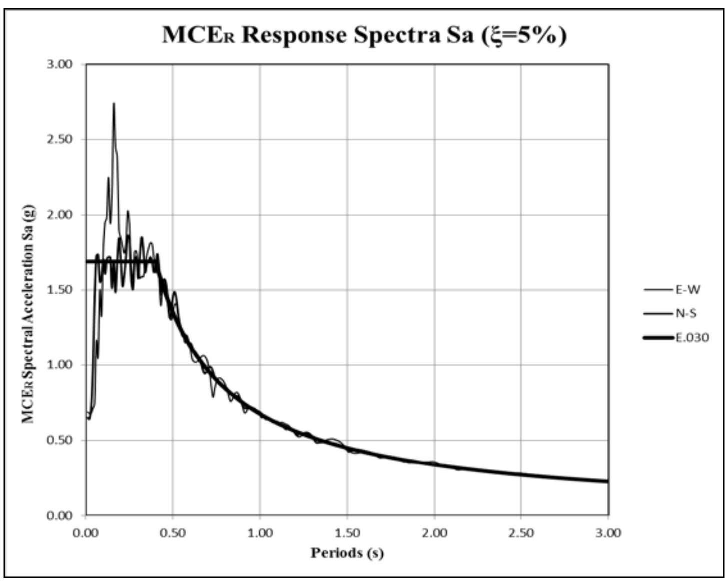

Fig. 5 – MCE_R Response Spectra of E.030 Peruvian Standard and
E-W and N-S components of 2010_Maule_Curico artificial seismic record

2.3. Dynamic analysis results from ETABS

Time history and response spectrum analysis of the isolated building with one, four and eight stories were performed using ETABS. For time history analyses, the structure was assumed to behave linearly while the nonlinear properties of the isolators were deemed to compute the maximum inelastic responses. On the other hand, response spectrum analyses were executed considering the effective stiffness k and damping coefficient c associated with the isolation system supporting the eight-story building - even though k and c depend on mass - because the maximum story shears and drift ratios obtained using adjusted values of these properties were extremely greater than those corresponding to time history analyses, especially at one-story and four-story cases.

Moreover, modal combinations CQC, SRSS and 0.25ABS+0.75ABS (this mixed variant is allowed in the Peruvian seismic code) [6] were utilized. However, in this particular case, an unusual modal superposition 0.5ABS+0.5SRSS provides results more consistent with those from time history analysis [8].

Tables 1, 2 and 3 show the results of the dynamic analysis. "Average values" are the averages of the maximum values obtained in each time history analysis while "Maximum values" are the greatest values computed among all such results. "Base" refers to the isolation level.

Table 1 – Maximum story shears (tonf)

Case	Story	Time history analysis				Response spectrum analysis	
		Average values		Maximum values			
		X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	1	131.34	130.64	138.23	138.83	109.72	109.42
	Base	247.62	244.33	250.30	249.52	247.51	247.21
4L	4	134.04	130.39	148.81	145.70	115.68	114.44
	3	244.21	238.70	260.17	272.16	241.56	240.46
	2	315.85	304.57	350.80	321.35	344.03	344.16
	1	366.00	363.66	422.93	374.19	428.10	430.55
	Base	393.99	422.58	428.12	440.77	504.23	508.85
8L	8	113.93	116.73	128.87	121.32	102.19	100.01
	7	230.50	225.19	260.33	246.04	214.32	211.07
	6	316.84	317.35	346.59	349.08	308.03	305.21
	5	358.94	395.50	370.03	430.60	381.24	379.44
	4	403.89	462.81	431.21	526.72	443.54	442.21
	3	463.07	513.60	501.17	612.27	513.30	513.31
	2	507.05	542.43	538.02	673.48	561.18	562.37
	1	543.03	574.29	586.31	711.89	592.71	596.28
	Base	574.69	577.66	616.35	700.26	642.68	646.50

Table 2 – Maximum story displacements (m)

Case	Story	Time history analysis				Response spectrum analysis	
		Average values		Maximum values			
		X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	1	0.0640	0.0673	0.0669	0.0750	0.1022	0.1022
	Base	0.0618	0.0651	0.0647	0.0730	0.1000	0.0998
4L	4	0.1674	0.1758	0.1951	0.1854	0.2332	0.2344
	3	0.1644	0.1727	0.1921	0.1820	0.2303	0.2308
	2	0.1587	0.1668	0.1865	0.1766	0.2230	0.2238
	1	0.1508	0.1592	0.1786	0.1686	0.2142	0.2173
	Base	0.1427	0.1509	0.1706	0.1595	0.2037	0.2055
8L	8	0.3119	0.3251	0.3485	0.4117	0.3444	0.3432
	7	0.3090	0.3214	0.3449	0.4073	0.3398	0.3390
	6	0.3043	0.3150	0.3391	0.3997	0.3322	0.3319
	5	0.2974	0.3058	0.3309	0.3889	0.3226	0.3229
	4	0.2884	0.2944	0.3202	0.3748	0.3111	0.3118
	3	0.2773	0.2834	0.3076	0.3582	0.3020	0.3028
	2	0.2641	0.2709	0.2926	0.3400	0.2893	0.2902
	1	0.2493	0.2575	0.2759	0.3220	0.2744	0.2790
	Base	0.2354	0.2449	0.2604	0.3060	0.2596	0.2611

Table 3 – Maximum story drift ratios

Case	Story	Time history analysis				Response spectrum analysis	
		Average values		Maximum values			
		X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	1	0.0008	0.0008	0.0008	0.0009	0.0007	0.0008
4L	4	0.0014	0.0015	0.0014	0.0016	0.0015	0.0017
	3	0.0022	0.0024	0.0023	0.0027	0.0025	0.0031
	2	0.0028	0.0029	0.0030	0.0031	0.0034	0.0041
	1	0.0027	0.0027	0.0030	0.0029	0.0035	0.0040
8L	8	0.0014	0.0015	0.0016	0.0016	0.0015	0.0018
	7	0.0023	0.0025	0.0026	0.0028	0.0025	0.0030
	6	0.0031	0.0035	0.0033	0.0039	0.0034	0.0042
	5	0.0035	0.0043	0.0036	0.0047	0.0041	0.0050
	4	0.0039	0.0049	0.0041	0.0057	0.0047	0.0057
	3	0.0043	0.0053	0.0046	0.0064	0.0052	0.0064
	2	0.0045	0.0054	0.0048	0.0068	0.0055	0.0067
	1	0.0041	0.0047	0.0044	0.0059	0.0049	0.0058

According to these results, maximum shear forces in the eight-story structure are always higher than those in the one-story and four-story buildings, and maximum story drift ratios of the under-construction structure are always lower than those of the eight-story building. Now, focusing on contrasting dynamic analysis results at each story-case separately, it is observed that maximum story displacements and drift ratios from response spectrum analyses are usually greater than the corresponding average values from time history analyses, but this tendency is somewhat altered when comparing with the maximum values. In contrast, maximum story shears from response spectrum analyses are generally lower than the respective average values from time history analyses in the upper half of the structure, a condition which is extended to the lower half when comparing with maximum values.

3. Generalization of the seismic analysis of base isolated buildings

The increment of the isolation system damping leads to the increase of higher mode contributions to story shear forces and story drift ratios. However, it is not possible to run the response spectrum analysis in ETABS taking into account this effect. Hence, the isolated shear beam model of Fig.1 was used to represent the building being studied and it was solved in order to obtain results which include the referred increase. Precisely, Tables 4 to 6 show the respective comparisons.

Table 4 – Maximum base shear V_b and first-story shear V_{st} (tonf)

Case	Story	ETABS				Shear beam model	
		Time history analysis Maximum values		Response spectrum analysis		Response spectrum analysis	
		X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	**1**	138.23	138.83	109.72	109.42	255.42	254.72
	Base	250.30	249.52	247.51	247.21	402.70	402.21
4L	**1**	422.93	374.19	428.10	430.55	569.41	572.67
	Base	428.12	440.77	504.23	508.85	564.90	570.07
8L	**1**	586.31	711.89	592.71	596.28	705.73	709.97
	Base	616.35	700.26	642.68	646.50	753.02	757.49

Table 5 – Maximum base displacement D_M (m)

Case	ETABS				Shear Beam Model	
	Time history analysis Maximum values		Response spectrum analysis		Response spectrum analysis	
	X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	0.0647	0.0730	0.1000	0.0998	0.1200	0.1195
4L	0.1706	0.1595	0.2037	0.2055	0.2353	0.2374
8L	0.2604	0.3060	0.2596	0.2611	0.2860	0.2876

Table 6 – Maximum first-story drift ratio Δ/H

Case	ETABS				Shear Beam Model	
	Time history analysis Maximum values		Response spectrum analysis		Response spectrum analysis	
	X Direction	Y Direction	X Direction	Y Direction	X Direction	Y Direction
1L	0.0008	0.0009	0.0007	0.0008	0.0012	0.0014
4L	0.0030	0.0029	0.0035	0.0040	0.0041	0.0047
8L	0.0044	0.0059	0.0049	0.0058	0.0051	0.0060

In general, the values of V_b, V_{st}, D_M and Δ/H from response spectrum analyses of the isolated shear beam model are similar or greater than the corresponding maximum values from time history analyses using ETABS. Nevertheless, it should be noted that there are some exaggerated values of seismic responses when applying the dynamic analysis to the shear beam model, especially when the building has one story.

Then, after studying the shear beam on a linear isolator model on a more realistic and deeper way than in the past [1] and proving its validity, Fig. 6 to 10 were constructed. Utilizing them it is possible to obtain speedily the most important seismic responses of any base isolated structure, even if those are not graphed. For example, V_b and V_{st} can be replaced in some established formulas of the equivalent lateral force procedure [9] to calculate the shear force at a specific story of an isolated building.

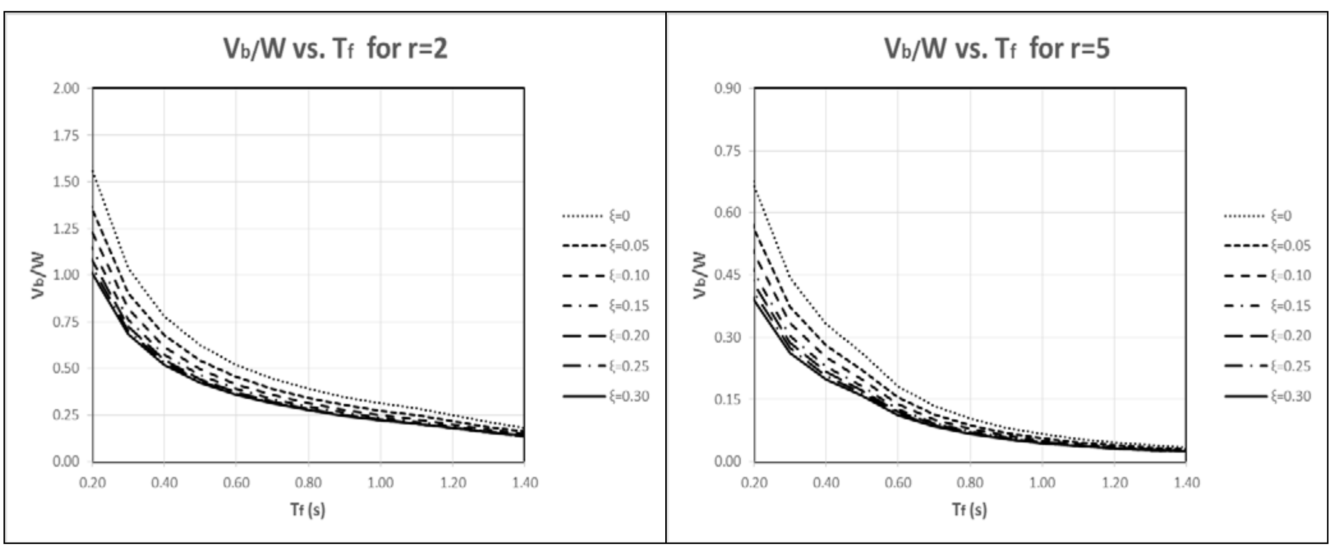

Fig. 6 – Maximum base shear V_b as a function of T_f, r, ξ and W (Mg)

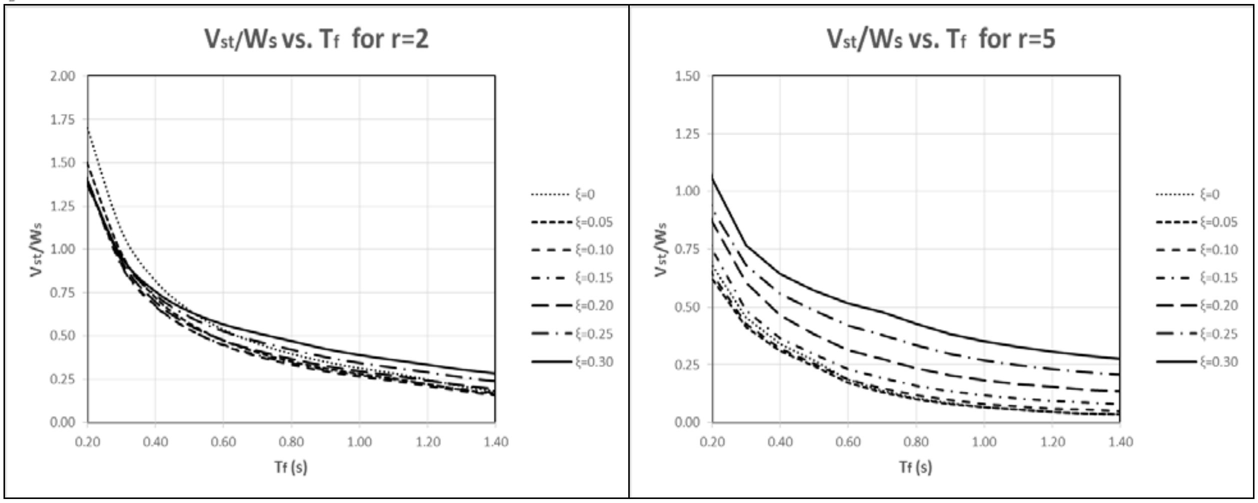

Fig. 7 – Maximum first-story shear V_{st} as a function of T_f, r, ξ and W_s ($M_s g$)

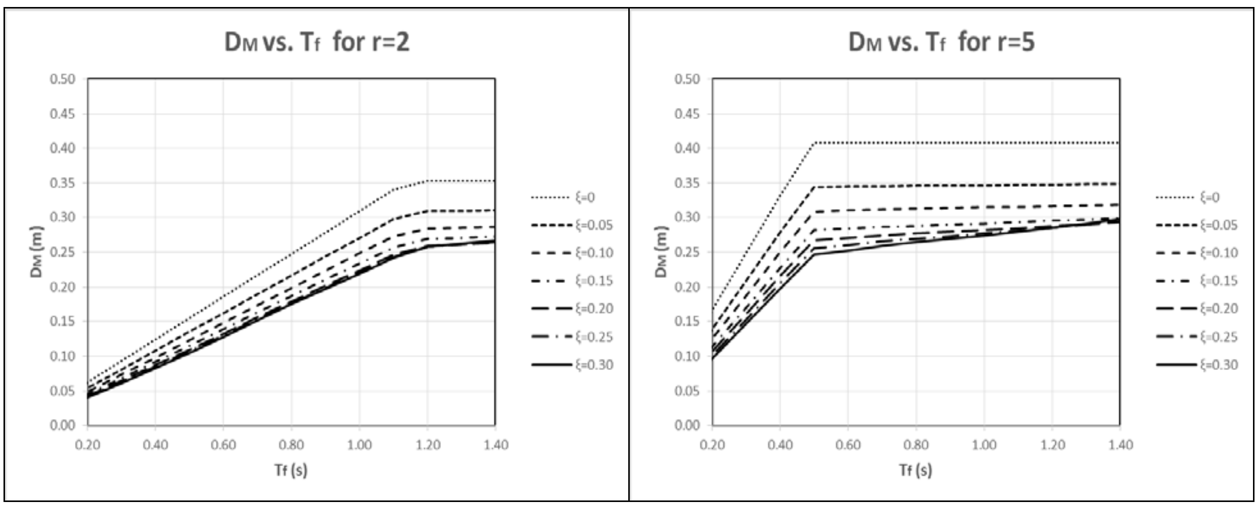

Fig. 8 – Maximum base displacement D_M (m) as a function of T_f, r and ξ

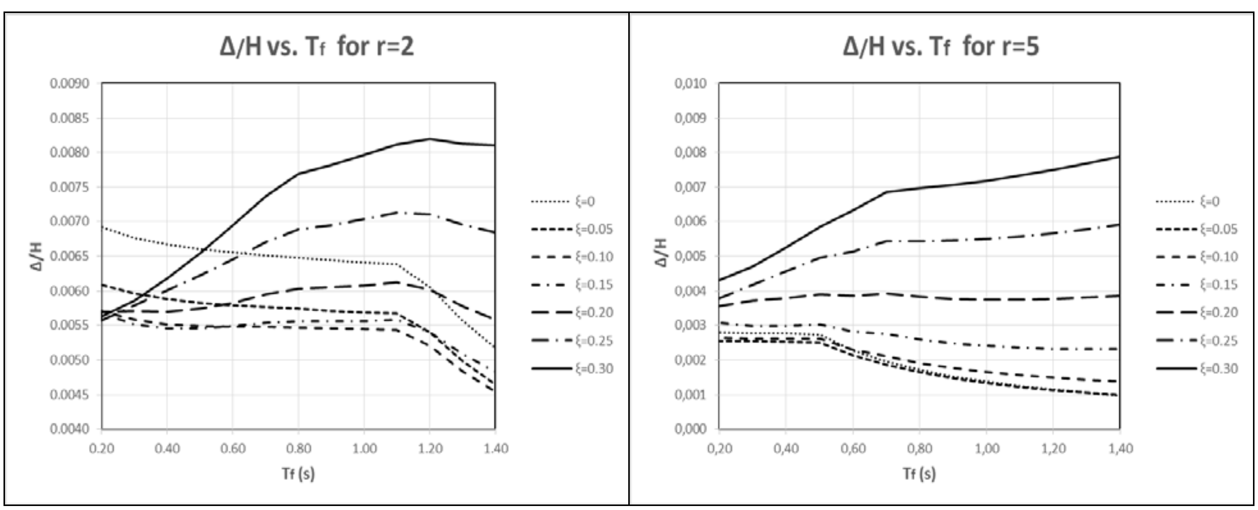

Fig. 9 – Maximum first-story drift ratio Δ/H as a function of T_f, r and ξ

4. Conclusions

To perform the seismic analysis of any base isolated building at different stages of construction, it is not necessary to adjust the effective stiffness k nor the damping coefficient c to the corresponding base displacement. Instead, design values of k and c computed for the completed building can be safely used.

The possibility of having shear forces in a partially constructed base isolated building which are greater than those acting on the complete structure is practically discarded. In addition, story drift ratios augment as the number of stories increases. Therefore, under-construction isolated buildings are generally well protected, even with larger margins than those at their final stage.

By performing the response spectrum analysis of the isolated shear beam model which represents the structure being studied, it was demonstrated that considering the contributions of the higher modes when isolation system damping is high leads to seismic responses similar or greater than those obtained from time history analysis. It overcomes the problem of having lower values of seismic responses when performing response spectrum analysis by utilizing computational programs.

Finally, some graphics that describe the dynamic behavior of the isolated shear beam model have been proposed to perform the seismic analysis of any base isolated building at different stages of construction. These charts will allow structural engineers to estimate the most important maximum seismic responses very quickly.

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