17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

PROPOSAL OF SEISMIC ISOLATION OF PERUVIAN ECONOMIC HOUSES THROUGH FREE-STANDING COLUMNS

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Abstract

Modern seismic protection systems, like base isolation, have proven to be effective reducing expected damage of buildings due to seismic events. Around the world, this technology had been applied more frequently to important buildings, however, there's no reference of its application to a massive use in low-rise buildings (economic houses). New studies of seismic protection systems, such as free-standing columns has been developed by researchers and would be applied to economic houses.

This article resumes the expressions developed by some researchers to evaluate the response of free-standing columns subjected to movement in its base, in particular type pulse signals. Also, in this paper it is evaluated the influence of the maximum horizontal acceleration on the base, the duration of the seismic signal and the effect of vertical acceleration, column size and slenderness on the seismic response of the oscillating columns.

Typical Peruvian signals have a frequencies content different to harmonic functions to impulsive signal, therefore the seismic response of free-standing columns could be very difficult to predict. The objective of this paper is to predict the seismic response of typical RC columns subjected to Peruvian record motions. Results indicate low rotations in rare earthquakes, concluding that free-standing columns could be applied to economic buildings trying to create a mechanism of seismic isolation.

Keywords: rocking isolation, seismic isolation, economic houses

1. Introduction

Seismic Isolation Technology has theoretically proven to be highly effective for mitigating expected damage in seismic events. However, in countries like the United States and New Zealand its use has been limited to important buildings such as hospitals or other essential buildings [1], seeking continuous functionality after a severe earthquake. The main reason for its limitation is its “high” initial cost compared to a conventional building, although they have already demonstrated in the field their benefit during a seismic event [2, 3].

Most low-cost Peruvian buildings correspond to the structural system of Masonry and Reinforced Concrete Walls [4]. These structural walls had already been tested to know about their seismic response [5, 6, 7]. Experimental results indicate that masonry walls present initial cracks at drift of 0.001 and reach severe damage at drift 0.005, which is the limit established by the Peruvian masonry code to repair actions [8].

In recent years, Peruvian Structural Engineers have proposed, in the current Peruvian Seismic Code [9], to protect essential buildings with Seismic Isolation Technology. On the other hand, researchers have discovered innovative protection systems, such as the free-standing column system [10, 11]. The approach of that system was born from the good performance demonstrated by the ancient monolithic temples and now has implications in the design of bridge columns [12]. This system consists in columns not connected to the ground, which support a high weight, that oscillates during the seismic movement and base their balance on their own gravity loads.

Makris [12] had investigated characteristics that affect the stability of free-standing columns when are subjected to horizontal and vertical seismic signals: (a) size; and (b) slenderness. In addition, results indicate that their seismic behavior is sensitive to local details of the seismic signals and the frequency domain of the dominant pulse. Two of their most important conclusions are that the free vibration response depends on the amplitude of vibration and that vertical acceleration has a minimal effect on the response.

The present article evaluates rocking response of free-standing columns to three representative Peruvian seismic signals. Results are variable due to the high frequency content of Peruvian seismic records. It will present the first evaluation of typical free-standing columns subjected to Peruvian earthquakes.

2. Theorical Framework

2.1. Motion equation of free-standing columns

Housner [13] began the development of dynamic equilibrium of free-standing columns. Their expressions were purely theoretical and based on the response of free-standing column to free vibration and harmonious forced movement. Later, some authors [14, 15] adapted numerical solutions from the Newmark and the Central Difference method to solve the dynamic equilibrium of these columns.

Fig. 1 presents the dynamic equilibrium of the free-standing column at the beginning of rocking movement in the base around O 'and O. The resulting motion equation for a positive turn is presented in Eq. (1).

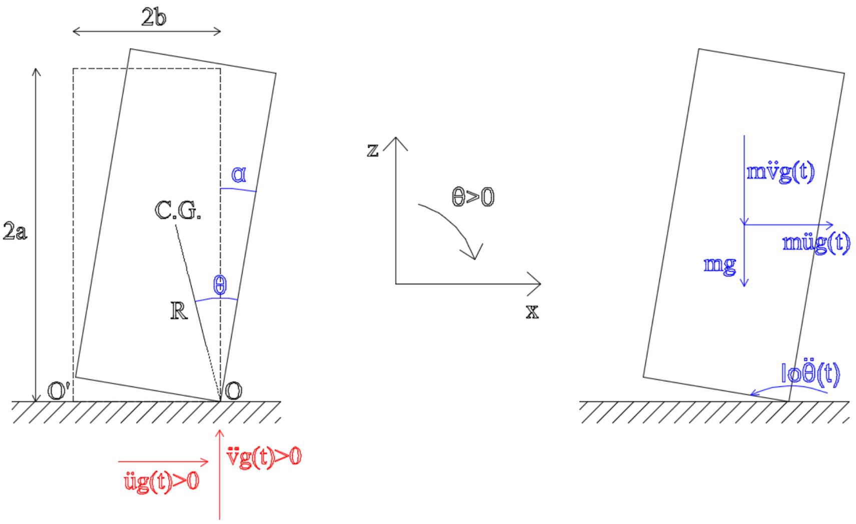

Fig. 1 - Geometric characteristics of a free column; and Dynamic swing column equilibrium [12].

$$I_0\ddot{\theta}(t) + mgRsin[\alpha - \theta(t)] = -m\ddot{u}_g(t)Rcos[\alpha - \theta(t)] - m\ddot{v}_g(t)Rsin[\alpha - \theta(t)] \quad (1)$$

Io = block rotational inertia; m = block mass; g = gravity acceleration; 2b, 2h, 2R = block thickness, size and diagonal; α = diagonal angle; θ(t) = flexural rotation; ug(t) = horizontal acceleration; and vg(t) = vertical acceleration of the free-standing column.

The rocking frequency of a free-standing column under free vibration is not constant, because in addition to the dimensions of the column, it depends on the amplitude of the vibration. The quantity p = √ (3g / 4R) is a measure of the dynamic characteristics of the column, which movement equation is presented in Eq. (2).

$$\ddot{\theta}(t) = -p^2\left\{\left(1 + \frac{\ddot{v}_g(t)}{g}\right)sin[\alpha sgn(\theta(t)) - \theta(t)] + \frac{\ddot{u}_g(t)}{g}cos[\alpha sgn(\theta(t)) - \theta(t)]\right\} \quad (2)$$

Rocking movement begins when the horizontal acceleration at the base reaches the value presented in Eq. (3).

$$\ddot{u}g > (1 + \ddot{v}g/g)\, g \tan\alpha \quad (3)$$

Also, free-standing columns won´t slide if the force generated by the horizontal acceleration doesn´t exceed the maximum friction force. To avoid slide, the minimum friction coefficient (u) should be as indicated in Eq. (4). In sine-type seismic signals, the block oscillates without sliding if the Eq. (5) is fulfilled.

$$u > |\ddot{u}g|/(g + \ddot{v}g) \quad (4)$$

$$u > \tan\alpha \quad (5)$$

2.2. Oscillating column behavior

Makris [12] describes two failure modes for oscillating columns: (a) lower mode: overturning with impact; and (b) superior mode: overturning without impact. In the first case, the column begins oscillation, returns to its initial position, however, the great speed causes the column to turn. In the second case, the column begins oscillation and the demand is greater than the restitutive force and the column can´t return to its original position and turns around. Fig. 2 shows the two types of failure of a 0.60m x 3.00m column for a sinusoidal type function with Tp = 0.30s.

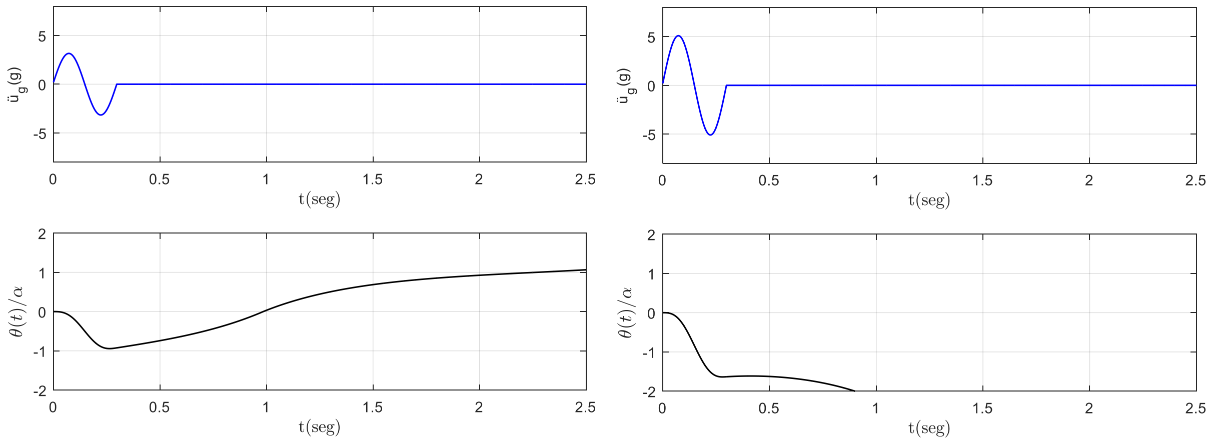

Fig. 2 - Failure modes for a rectangular column: (left) Overturning with impact; and (right) Overturning without impact.

In slender columns there is a safety margin between lifting and turning. This safety margin increases when the size of the column is increased, as when the column decreases its slenderness.

If there’s no turning, the column begins a rocking movement over corners of its base as shown in Fig. 3. Also, after an impact with the base there is a reduction in the amount of movement and kinetic energy, presented in the Eq. (6).

$$r = \left(\frac{\dot{\theta}_2}{\dot{\theta}_1}\right)^2 = \left[1 - \frac{3}{2}\sin^2(\alpha)\right]^2 \tag{6}$$

After a free-standing column is subjected to forced movement, it begins its free movement and the velocity is reduced after each impact until returning to rest. This factor takes a fundamental role in the dynamic response and is the unique responsible of the damping. If column is slenderer, this reduction factor will be greater.

Makris [16] described the effect of the weight on the response of free-standing columns and conclude that a column with a greater weight above will have greater seismic capacity. That study establishes that the weight reduces the reduction coefficient and increases the frequency parameter.

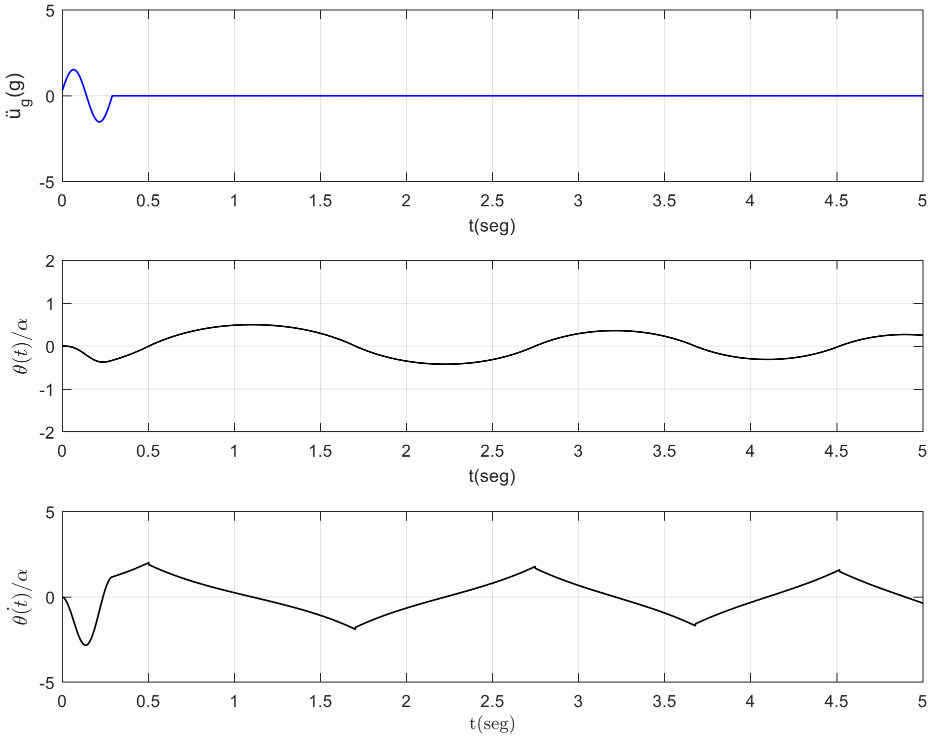

Fig. 3 - Seismic behavior of a rectangular column of 0.60m x 3.00m at harmonic load of maximum ground acceleration of 1.5g and Tp = 0.30 s.

2.3. Maximum horizontal acceleration influence and pulse duration

Makris [12] concluded that seismic response of free-standing columns is sensitive to local details of the seismic record and a dominant frequency of a distinguishable pulse. Baker [18] related American seismic signals as pulse type signals: sine function, Symmetric Ricker and Anti-symmetric Ricker. These pulse-type functions are related to a maximum ground acceleration (ap), and the pulse duration (Tp). Figure 4 shows the pulse forms evaluated by Baker for a period Tp = 2.0 s.

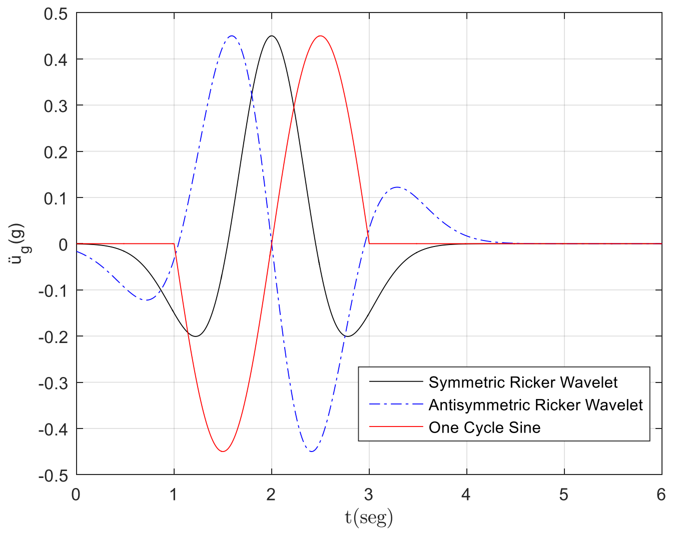

Fig. 4 - Pulse type functions

A typical signal of the North American earthquakes is presented in Figure 5, from which an anti-symmetric wavelet type of ap = 0.42 g and Tp = 0.62s is extracted.

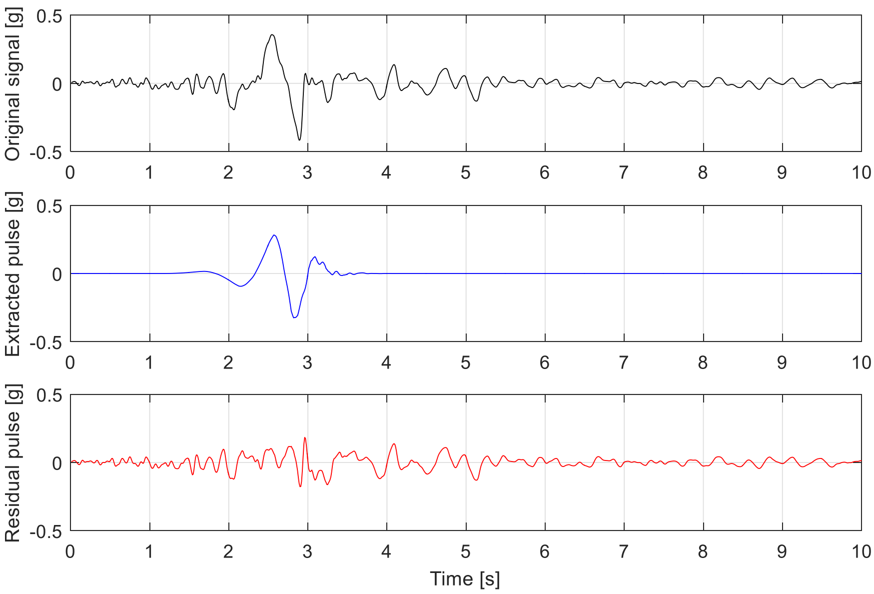

Fig. 5 - Pulse signal extraction from Coyote Lake 1979 earthquake, Gilroy Array station no.6.

Makris [12] identified the Pulse Energy Length scale (Le = ap.Tp^2) as the predominant factor in the seismic response. That investigation concluded that a harmonic movement with a certain PGA will generate a greater turn to the system if it prolongs its duration (similar to a static load). Earthquakes such as Kobe (ap = 0.5g, Tp = 0.66s.), Coyote Lake (ap = 0.35g, Tp = 1.00s.) and Lefkada (ap = 0.5g, Tp = 0.50s.) presented values of Le between 1.23m and 3.43m.

Fig. 6 shows a spectrum of accelerations necessary to the overturning of a free-standing column with tan (α) = 0.25 and p = 2.14 rad/s. The red zone indicates that column has an impact before overturning (until a wp/p = 7.3). It corresponds to the case of low frequencies or high periods. The blue zone indicates that the column would fail without any impact and corresponds to high demand frequencies.

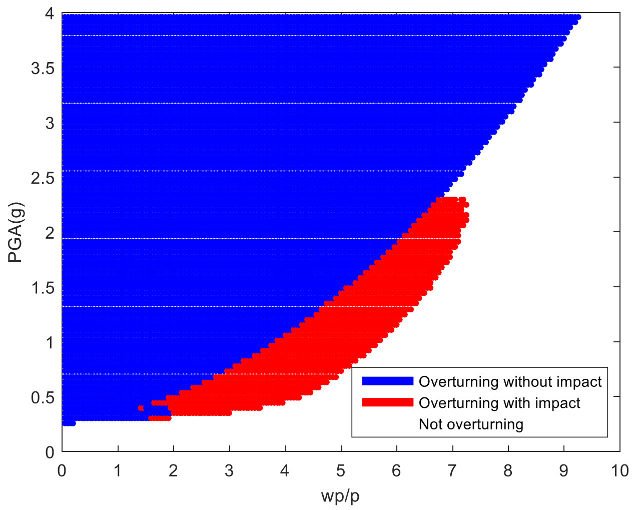

Fig. 6 - Acceleration spectrum for a free-standing column (p = 2.14 rad/s) in rocking motion with tanα = 0.25 when subjected to a sine oscillation pulse.

Accelerations that cause the collapse in the zone of high periods or low frequencies is much lower than accelerations in lower periods. For example, considering two different periods (Tp) of 0.50 s. and 1.00s, then the frequencies relations are 5.87 and 2.94 and their correspondent failure accelerations are 11.30 m/s^2 and 3.46 m/s^2, respectively. It means than an increasing to the double of period corresponds to a decreasing of capacity to the quarter. It´s related to Makris's criteria [12] to propose the pulse Energy Length scale as a function proportional to the maximum acceleration and proportional to the square of the movement period.

2.4. Slenderness and size effect

Makris [12] investigated the effect of size and slenderness in free-standing columns. Also, the increase in size always increases the stability of the system and can lead to a change of failure mode.

Fig. 7 shows the accelerations that would generate the turning of columns of width 2b = 1.0m with different values of diagonal and movement period.

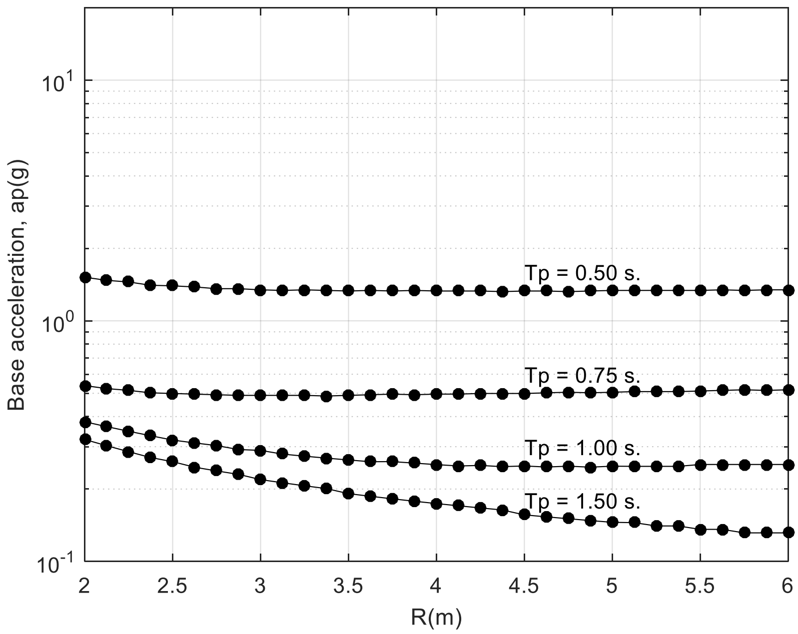

Fig. 7- Turning acceleration diagrams due to a sine-type pulse necessary to turn a free column with base 2b = 1.0 m.

According to Fig. 7, for slow movements (large Tp and small wp), rotational inertia is not very helpful in the seismic response. Then slender column will have a worse seismic performance, but size of column isn't an appreciable factor in the answer. For fast movements there is no relationship, there isn't a trend and even a slender element may need greater acceleration to fail.

3. Analysis and results

3.1. Peruvian seismic signals as harmonic loads

Frequencies content of Peruvian seismic records are quite different to the correspondent to North America, which are more similar to pulse-type records. Fig. 8 presents the Pisco 2007 seismic record, which presents only small zones where the record can be approximated to a harmonic load. It means that this records can´t be approximated to pulse-type records.

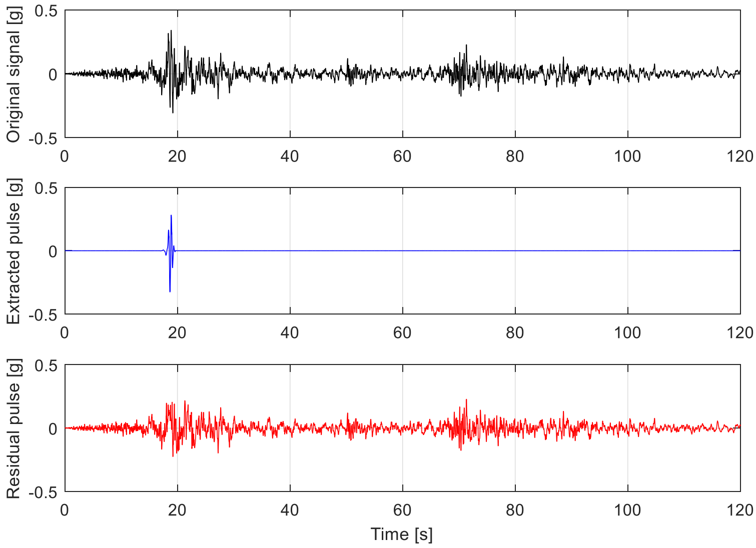

Fig. 8 - Pulse extraction (PGA = 0.325g, Tp = 0.658s.) of the Pisco 2007 earthquake (PGA = 0.341g).

Pisco seismic signal reaches an Energy Length factor of 1.28m, lower than the pulse type earthquakes, but the great frequencies content could be more significant in the response.

3.2. Comparison between response to seismic excitation and harmonic excitation

Fig. 9 presents the column response to Pisco 2007 seismic record (scaled to Peruvian seismic design spectrum) and to a pair of pulse movements (type Ricker anti-symmetric and Ricker symmetric) with Tp similar to the seismic record.

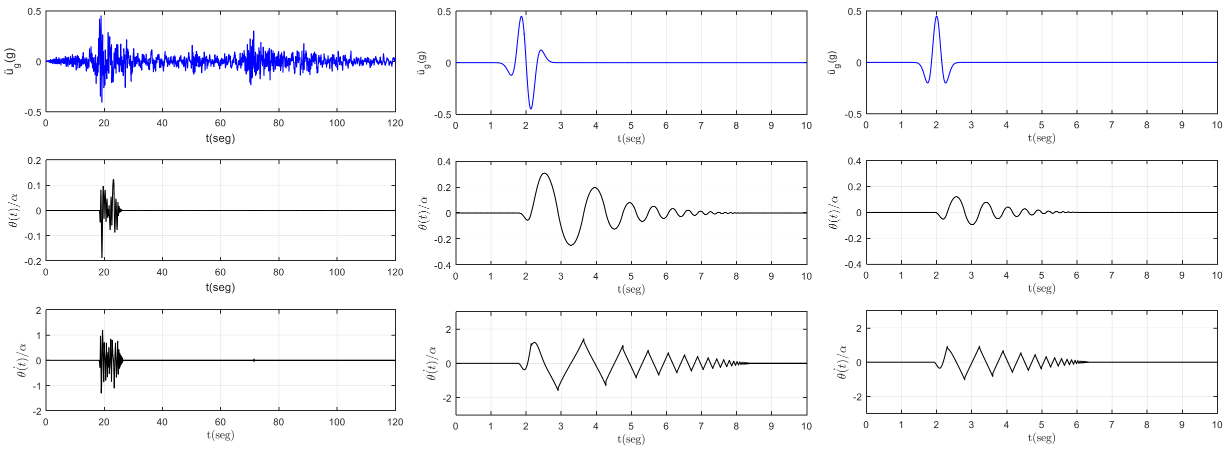

Fig. 9 - Seismic response to: (a) Pisco 2007 scaled (PGA = 0.45 g); (b) Anti-symmetric Ricker signal (PGA = 0.45g, Tp = 0.658s); and (c) Symmetric Ricker Signal (PGA = 0.45g, Tp = 0.658s).

Maximum rotation reached by Pisco 2007 seismic record corresponds to an intermedia value between rotation reached by harmonic signals. Fig. 10 shows the maximum responses of 0.80m x 3.00m and 0.60m x 3.00m to three representative Peruvian earthquakes. For the 0.80m x 3.00m column, the maximum rotation doesn´t exceed 35% of the angle to block failure before reaching a maximum acceleration. The 0.60m x 3.00m column presents failure cases for PGA between 0.9 and 1.0g.

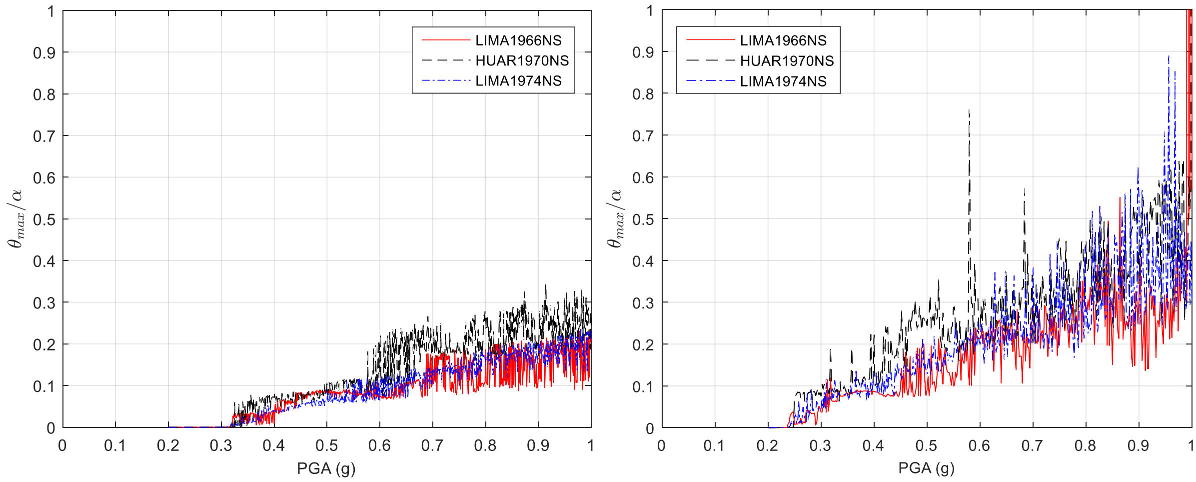

Fig. 10 - Maximum rotation response for different intensities of Peruvian earthquakes: (a) Column 0.80m x 3.00m; and (b) Rectangular column 0.60m x 3.00m.

3.3. Approximation to seismic response

As mentioned above, the Peruvian seismic signals have no similarity to North American signals, however, results can be tried to predict by pulse signals. An approximation can be made considering a period, Tp, between 0.3 and 0.6s. In this range, typical columns of 0.80m x 3.00m (p = 2,177 rad/s) generates a ratio frequency, wp/p, between 4.81 (Tp = 0.60s) and 9.62 (Tp = 0.30s). Fig. 11 shows the response of a rectangular column 0.80m x 3.00m to sinusoidal signals of one entire cycle, and one entire cycle and medium.

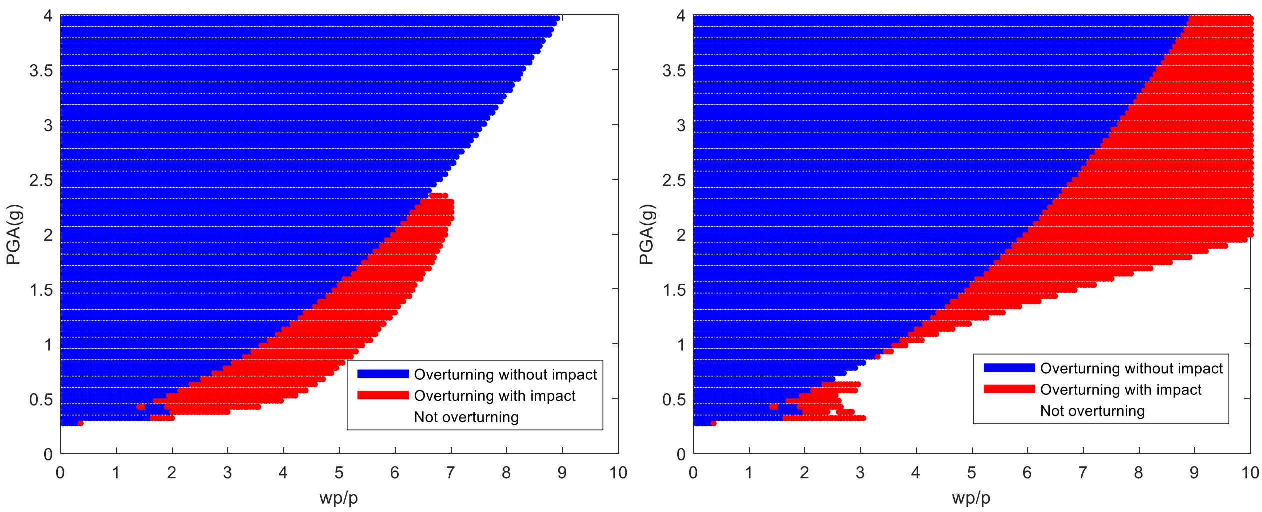

Fig. 11 - Oscillating 0.80m x 3.00m column response spectrum: (a) Entire cycle sinusoidal signal; and (b) Entire cycle and medium sinusoidal signal.

For a sinusoidal signal of an entire cycle, the column 0.80m x 3.00m begins to fail at PGA of 0.73 g and 4.55 g for Tp period of 0.60 s and 0.30 s, respectively. PGA of failures in sinusoidal signal of a cycle and a half correspond to 1.19 g and 1.94 g for the periods in analysis. Given the randomness of the seismic load, we can consider the envelope of both cases, and obtain that failure accelerations of 0.73 g and 1.19 g can be related to signal with Tp = 0.60s and Tp = 0.30s, respectively.

Fig. 12 shows accelerations correspondent to failure of rectangular columns of width 0.80m, changing the dimension of the diagonal R of the block. It is observed the decreasing in the capacity when the period is increased. For the 0.80m x 3.00m column, the capacity decreases to 16% for the entire cycle sinusoidal signal and decreases to 61% for the entire cycle and medium sinusoidal signal.

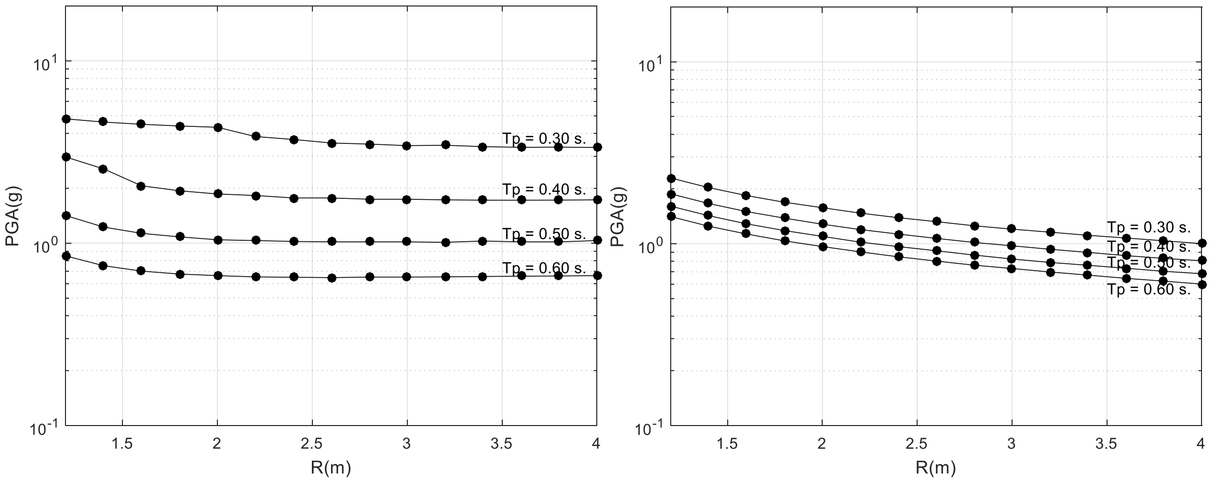

Fig. 12 - Oscillating column response spectrum with base 0.80m: (a) Entire cycle sinusoidal signal; and (b) Entire cycle and medium sinusoidal signal.

Results indicate that the 0.80m x 3.00m column would have turned for a Peruvian seismic record of PGA of 0.73 g.

4. Conclusions

According to the results obtained for pulse type signals and the good behavior presented in typical ancient Greek temples, the free-standing columns constitute an option to reduce seismic damage.

Typical 0.80m x 3.00m columns begin to oscillates at PGA of 0.3g (greater than the expected demand for an occasional earthquake), when is subjected to Peruvian seismic records or representative signals with similar frequencies. At acceleration corresponding to a rare earthquake (PGA of 0.45g), columns reach a maximum rotation of 10-20% of the block diagonal angle.

Rocking isolation could be checked through experimental tests for a proposal of seismic isolation of economic houses supported by free-standing columns. Results should be studied for systems with two or more degrees of freedom, considering the weight of a common building. This study contributes as state of art to the development of that project.

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