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PROTECTING NUCLEAR INFRASTRUCTURE FROM EARTHQUAKES THROUGH VIBRATING BARRIERS

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ABSTRACT

This paper aims to establish the efficiency of a new device called Vibrating Barrier or (ViBa) (Figure 1) in protecting nuclear containment (NC) structures from earthquakes. According to the original authors of the ViBa paper, ViBa is "a massive structure, hosted in the soil and detached from the existing building, calibrated for absorbing portion of the ground motion input energy" [1] . The NC structure can benefit from the ViBa while not necessarily being attached to it to reduce the peak acceleration and displacement. ViBa works on the principle of structure soil structure interaction (SSSI), [2]. The scope includes building a FEM model of a NC structure on a raft foundation with soil. This model is used to benchmark the behaviour of the structure without a ViBa, which is referred to as an "uncoupled structure", while undergoing seismic loading. After that, the ViBa is tuned using Den Hartog's optimum expressions, coupled with the structure and analysis is run again. The results of the dynamic analysis for the coupled structure are compared to that of the uncoupled structure and a conclusion is drawn. Furthermore, parametric testing results are provided for five parameters: the ViBa-structure mass ratio; the depth at which ViBa is installed; the distance between the ViBa and NC structure; and finally the possibility to split the lumped mass of the ViBa into multiple smaller masses around the structure.

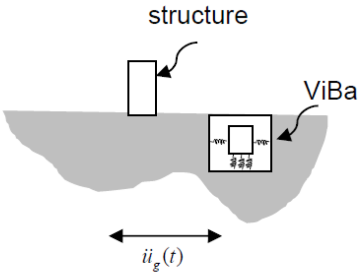


Figure1 Conceptual sketch of the ViBa

INTRODUCTION

Using Nuclear power to generate electricity is expensive and its infrastructure takes extended periods of time to come to life. Additionally, it is a risky business to get rid of the nuclear waste as well as environmentally taxing. That is without factoring in potential disasters associated with it. The world still remembers Chernobyl 1986 and Fukushima Daiichi 2011.

While a lot have changed to reduce the probability of operator error to reproduce events such as Chernobyl, the question remains, is it possible to protect power plants against earthquakes? After all, Fukushima Daiichi disaster in 2011 occurred due to the strongest earthquake Japan have seen for over 1000 years. To answer this question, the following paper is an early attempt to substantiate the efficiency of using a novel device called Vibrating Barrier (ViBa) to protect nuclear power plants from earthquake action.

ViBa utilises the structure-soil-structure interaction as the basis on which its concept is built on. One of the pioneers of this field is George W. Housner [3] who studied soil amplification and SSI. Furthermore [4] studied the influence of masses on each other in an elastic subspace and how these masses affect each other's dynamic behaviour.

The Nuclear Containment Structure

As a case study to evaluate the effectiveness of ViBa, a nuclear containment structure taken from [5] is considered; however, the structure in this case is not assumed to be embedded in the soil but is placed flush with the ground level. The dimensions used in this study are shown in Table 1.

Table 1: Geometry of the nuclear containment as well as the ViBa

NC structure inner radius	25.8 m
Total Height (including basement)	59 m
Wall thickness	1.07 m
Basement thickness	1.5 m
Basement height	12.9 m
Foundation Length	77 m
Foundation Width	77 m
Foundation Depth	3.1 m
ViBa walls/floor thickness	1.5 m
ViBa location from the NC	Varies

Convergence Study

The considered nuclear containment is modeled using commercial finite element (FEM) software. The first step in developing a working model in FEM is to carry out the simple test of convergence study. Convergence studies usually start with a simple model with a coarse mesh. Then, as the mesh gets finer and more complex, the most critical parameter is obtained every time and compared to the first value. In this study, the controlling parameter is the structure's natural period (T). Table 2 below summarises this simple task to ensure that no major errors are present at this stage of the study. It is noted that the natural period gets more accurate and no major changes occur in the natural period of the structure as the mesh get finer. Figure 2 shows how the mesh gets more complex as the number of elements increase.

Table 2 Convergence Study

Structure	No. of Area Elements	Natural period T (s)
1	128	0.14297
2	256	0.14486
3	384	0.14525
4	512	0.14538

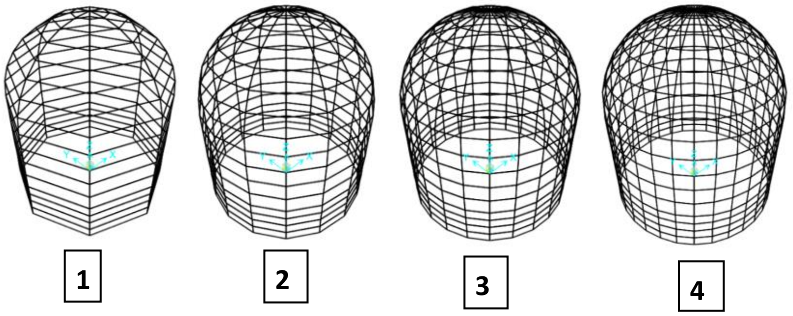


Figure 2 Structures 1,2,3 and 4 used for the convergence study

Modelling of ViBa and Setting Optimum Tuning Values

ViBa can be modelled as SDOF system where an oscillating mass is connected to a spring and a damper. ViBa mass is assigned at the free joint as a joint mass, and a roller support is provided in that location to prevent movement in the vertical direction.

Den Hartog's optimum expressions are used to determine the stiffness of the spring and damping coefficients of the ViBa. These values are then fed to the model in SAP2000

ViBa frequency ratio, $V = \frac{\sqrt{1+0.5\mu}}{1+\mu}$

Damping ratio, $\zeta = \sqrt{\frac{\mu(1+0.75\mu)}{4(1+\mu)(1+0.5\mu)}}$

Optimum stiffness coefficient, K-opt = $V^2 \omega^2 m_D$

Optimum damping coefficient C-opt = $2*\zeta*V*\omega*m_D$

To get the optimum connection(spring) length:

$\omega_n = 2 *\Pi*f$

$f_{-opt} = 1/1+\mu$

$\omega_D = \omega_n * f_{opt}$

$\omega = \sqrt{g/l}$

Where:

f_{opt}: Optimum frequency of the coupled system

μ: Mass ratios between the ViBa and the host structure
ωD: Natural circular frequency of the ViBa
ωN: Natural circular frequency of the structure (before coupling)
mD : Mass of the ViBa
g: gravity acceleration 9.81m/s2

Using the above expressions yield the tuned values for the optimum stiffness coefficient (K-opt), damping coefficient (C-opt), and connection length. Some key points worth mentioning here are that the ViBa is modelled in a trench under the surface of the ground at a certain depth and the trench walls are modelled as C40/50 concrete shell elements.

The Soil

The soil is modelled following equivalent elastic solids. Table 3 below define the geometry and the properties of the soil used in this study. The soil properties data are taken from [15].

Table 3 Material property details

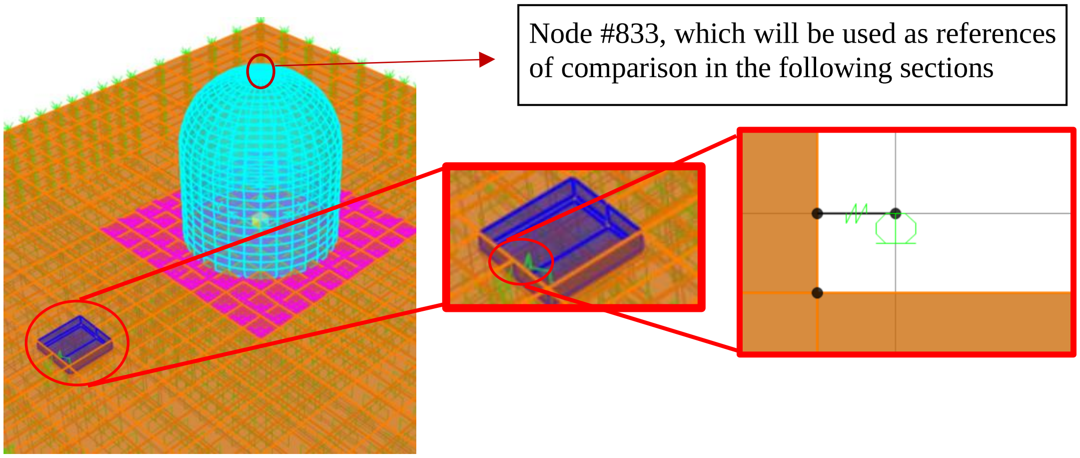
Properties	Soil	Mat Foundation	NC concrete
Unit Weight kN/m3	17.66	25.0	25.0
Modulus of Elasticity (kPa)	$1.26*10^6$	$35*10^6$	$35*10^6$
Poisson's Ratio	0.4	0.2	0.2

RESULTS

Results demonstrate that the ViBa is capable of enhancing the behaviour of structures under earthquake actions. However, the degree to which the ViBa affects the behavior is dependent on the earthquake. This section will demonstrate the variance that occurs while considering different earthquakes. The author would like to mention a disclaimer that the tuning of the ViBa discussed earlier plays a pivotal role in the results and that drastic change in the outcome is possible when different tuning expressions are used.

Earthquake Selection And Coupling Locations

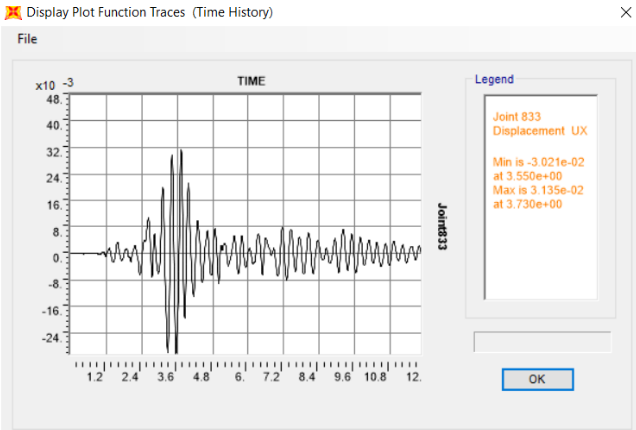
To measure the efficiency of ViBa, the uncoupled structure is first analysed against selected earthquake motions, after that, the ViBa is introduced, and the same analysis is performed again. Furthermore, a benchmark node is chosen to be the node where the highest acceleration occurs during the earthquake motion; however, in the original research [6], the authors provided the full table for all the nodes. Here, the benchmark node is number 833, located at the apex of the dome as shown in Figure 3 below. The selected earthquake motions are El Centro, in the US, Altadena in the US, and Coralitos also in the US.



Node #833, which will be used as references of comparison in the following sections

Figure 3 A model to demonstrate the NC structure with foundation, ViBa, and the soil. The ViBa walls coloured blue

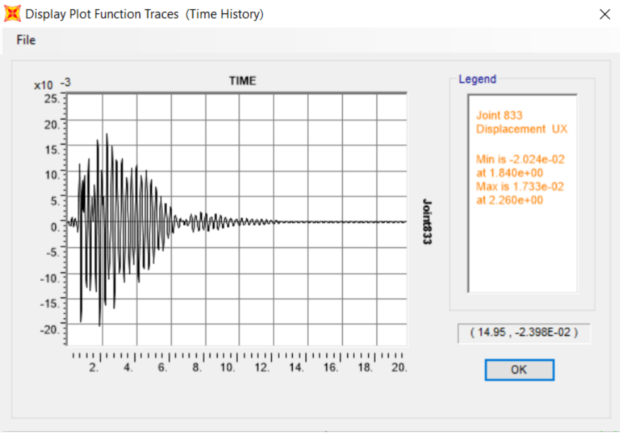
Upon running the time history analysis for the uncoupled structure using El Centro ground motion, it is found that the max relative displacement of node 833 in the negative X direction is 3.021 * 10^{-2}m (or 30mm) at 3.55 seconds. Whereas the max relative displacement in the positive X direction is 3.135 * 10^{-2}m (31mm) at time 3.73 seconds from when the ground motion started; this is depicted in Figure 4. Additionally, Figure 5 show the same but for the Coralitos ground motion.



Joint 833
Displacement UX

Min is -3.021e-02
at 3.550e+00
Max is 3.135e-02
at 3.730e+00

Figure 4 Relative displacement of node 833 under El Centro earthquake



Joint 833
Displacement UX

Min is -2.024e-02
at 1.840e+00
Max is 1.733e-02
at 2.260e+00

(14.95 , -2.398E-02)

Figure 5 Relative displacement of node 833 under Coralitos earthquake

Impact Of Distance Between ViBa And The Host Structure

One of the parameters that the efficiency of ViBa is tested for is the effect of distance from the host structure which the ViBa is meant to protect. In this study, the efficiency of the ViBa is measured based on two variables: the absolute maximum joint acceleration and the relative maximum joint displacement. Figure 6 demonstrates the result of structural displacement of node No.833 when the ViBa is coupled at location 1, while Table 4 below records the performance of the ViBa under El Centro earthquake at different locations of ViBa. The resulted values of the coupled structure are compared to those of the uncoupled and presented with respect to the location of ViBa. For example, the max. displacement of the uncoupled structure is 0.0313m (in node 833) and the max. Joint acceleration is 17.0m/s^2. However, once the structure is coupled with the ViBa at location 1, it found that the max. displacement is 0.0222m and max. acceleration is 12.554m/s^2 which is a reduction of -29% and -26% respectively. In the same manner, the table can be read for location 2 and 3.

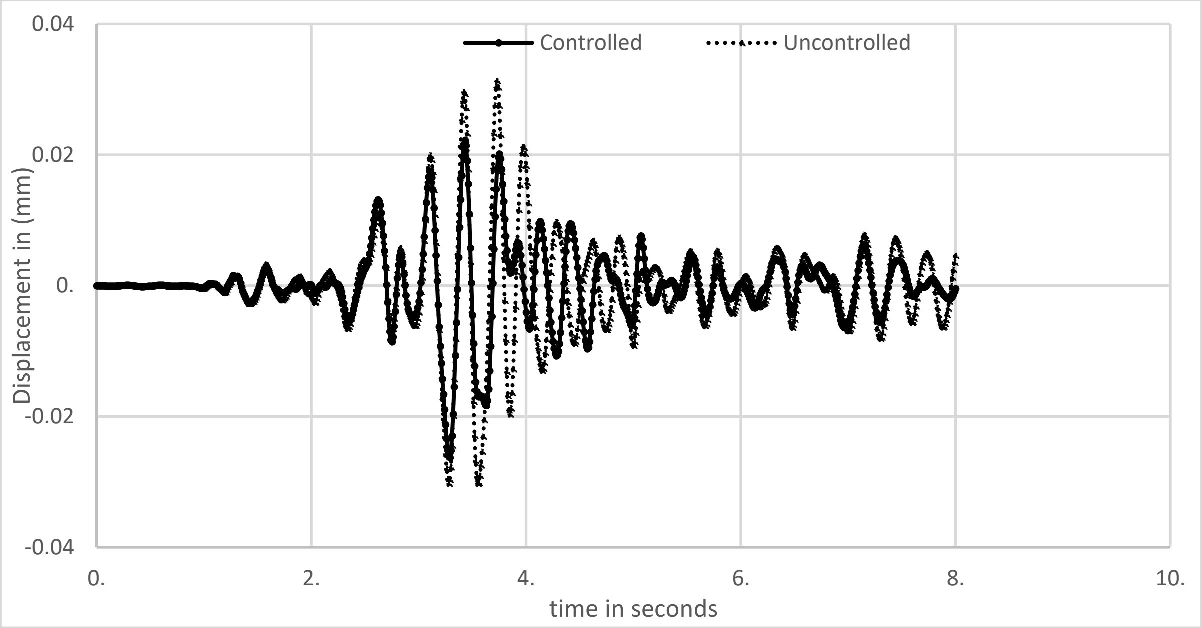


Figure 6: Comparing the coupled vs. uncoupled structural displacement at the node 833 under El Centro

While table 4 demonstrates results of node #833 only, the original research [6] includes tables in the appendix to provide information for numerous nodes to show a more representative result.

Table 4: viba efficiency under El Centro -earthquake – joint #833 Reduction in %

Variable	Location 1	Location 2	Location 3
Max joint displacement (m)	-29%	-12%	-6%
Max joint acceleration (m/s2)	-26%	-5%	-2%

The same is performed for the Altadena earthquake in Table 5 and Coralitos record in Table 6; however, it can be seen that ViBa was not as successful in mitigating the acceleration or displacement as for the case of El Centro record. Here, the three locations proposed are shown in Figure 6.

Table 5: ViBa efficiency under Altadena earthquake - joint #833 Reduction in %

VARIABLE	LOCATION 1	LOCATION 2	LOCATION 3
MAX JOINT DISPLACEMENT (M)	-3%	-1%	0%
MAX JOINT ACCELERATION (M/S2)	-3%	-1%	0%

It is evident from the above tables that the ViBa is not running efficiently under the current settings because its outcome is inconsistent across the different earthquakes, potentially because different tuning is required for different earthquake motions.

Table 6: ViBa efficiency under CORRALITOS earthquake- joint #833 Reduction in %

VARIABLE	LOCATION 1	LOCATION 2	LOCATION 3
MAX JOINT DISPLACEMENT (M)	-26%	0%	1%
MAX JOINT ACCELERATION (M/S2)	2%	-1%	-1%

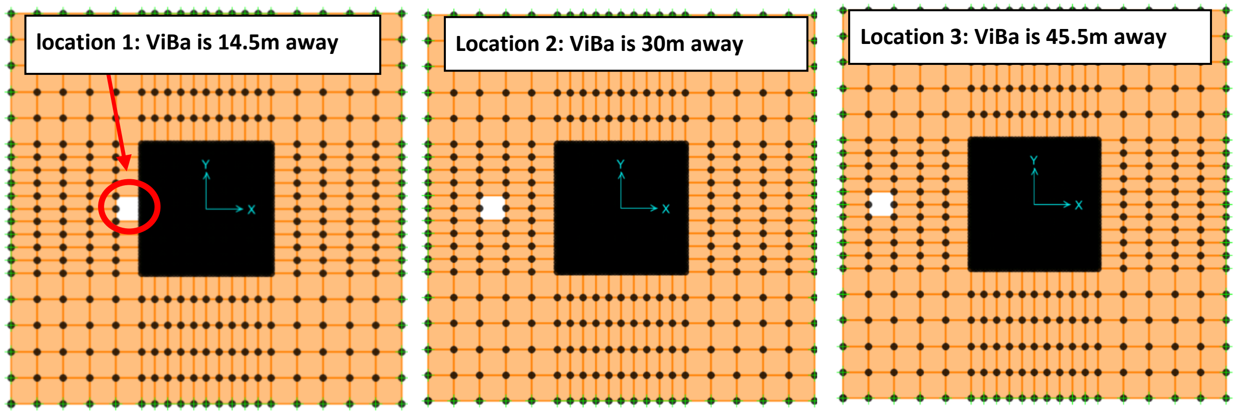


Figure 6 The Three locations of ViBa coupling included in this study

Impact of the depth at which the ViBa is buried at

Analysis demonstrates that the performance of the ViBa peaks when it is placed at 3m below the ground level (as the main structure is on the ground level). At any other depth, the performance deteriorates depending on how far the ViBa is placed from the benchmark point of 3m. It is expected that this benchmark distance is related to the tuning condition as well as other factors related to the host structure (with which the ViBa is coupled), however this was not tested in this study as only one factor was changed at a time. Table 7 below demonstrates how the ViBa performs at different depths.

Table 7: optimum depth of ViBa from surface level under El Centro-Reduction in %

Variable	At surface	2m	3m	4m	6m	9m
Max Joint displacement (m)	-18%	-24%	-29%	-23%	-26%	-23%
Max Joint Acceleration (m/s2)	2%	-7%	-26%	-8%	-15%	-12%

Impact Of ViBa-Structure Mass Ratio(µ)

In this section, comparison between the different ViBa-Structure mass ratios is put to test to gauge its impact on the performance of the ViBa. Keeping in mind that µ=0.5 means that the ViBa has 50% of the weight of the structure it is protecting. It is found that when a structure goes under El Centro ground motion, a higher mass ratio deteriorates the performance as the reduction in max joint displacement goes from 29% to 21% when mass ratio (µ) jumps from 0.5 to 1.0. The same can be noticed with the max joint acceleration (from reduction of 26% to 6%); see Table 8. Whereas in the case of Coralitos ground motion, increasing the mass ratio deteriorates the performance of displacements more than the acceleration; see Table 9 below.

Table 8: Impact of ViBa-Structure mass ratio under El Centro - location 1 Reduction in %

Variable	µ=0.5	µ=1	µ=1.5
Max Joint displacement (m)	-29%	-21%	-29%
Max Joint Acceleration (m/s2)	-26%	-6%	3%

Table 9: Impact of ViBa-Structure mass ratio under CORALITOS - location 1 Reduction in %

Variable	µ=0.5	µ=1	µ=1.5
Max Joint displacement (m)	-26%	-10%	-3%
Max Joint Acceleration (m/s2)	2%	2%	3%

Lumped versus multiple mass(s)

One of the major pitfalls of Viba is its massive weight, thus it would be natural that this issue is addressed in this paper. To this end, the author aimed to measure the efficiency of the ViBa when a single mass is used versus multiple scattered masses (or ViBas). The mass assigned to the ViBa in this study is 40881 tons as a single lumped mass. This single mass is spilt into 2 then into 4 masses, and the analysis is performed every time; then the results are compared to the performance of the single mass. It is worth mentioning that the distance between the ViBas and the structure is kept uniform and the required tuning is also done depending on the case. For example, the tuning of 2 masses is different than the 4 masses. It is found that the ViBa performs better with the single mass as opposed to multiple masses is considered. For instance, splitting the single large mass into two equal masses (50% each) yield adverse action in terms of displacement where the host structure experiences increase in the displacement measured when compared to the uncoupled case. Accelerations on the other hand had reduced efficiency of 14% compared to 26%. For the purposes of this variable, all testing is conducted under El Centro earthquake and ViBa is coupled at location 1. The results are tabulated in Table 10 below.

Table 10: Measuring the influence of single mass versus multiple masses under El Centro Earthquake. Reduction in %

Variable	**1 mass**	**2 masses**	**4 masses**
Max Joint displacement (m)	-29%	5%	14%
Max Joint Acceleration (m/s2)	-26%	-14%	-6%

Figure 8 below demonstrate the locations of the multiple masses/ViBas used in this section of the study.

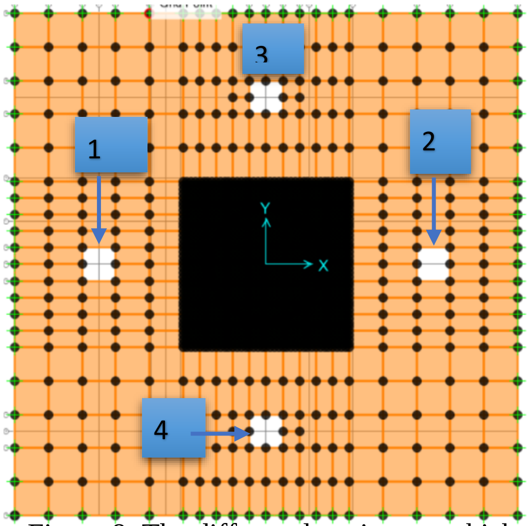


Figure 8: The different locations at which the ViBa is coupled with the host structure

Stresses and forces

To demonstrate the effect of ViBa on stresses and forces on the structure, the forces of the coupled structure are compared to those of the uncoupled. The max element force, element joint force and element stresses experienced by the structure are 2802kN/m, 11583kN and 2091kPa respectively. When compared to the results of the coupled structure, this yields the reductions shown below in Table 11. The results shown below are that of El Centro's ground motion results. Furthermore, it is no coincidence that location 1 yields the highest reduction of stresses; that is of course linked to the max reduction in displacement and acceleration seen in earlier results.

CONCLUSION

Table 11 - ViBa efficiency in reducing Max element forces and stresses under El Centro
Reduction in %

Variable	Location 1	Location 2	Location 3
Element forces (KN/m) -F11	-26%	-6%	-2%
Element joint forces (KN) -F1	-27%	-8%	-5%
Element stresses (KN/m2) S11Top	-28%	-12%	-5%

This paper discusses the potential of using a novel device, the Vibrating Barrier (ViBa), for tackling the problem of protecting nuclear infrastructure from ground motions. The ViBa reduces the stresses on a structure by reducing the acceleration and displacement during the ground motion. In this study, it is demonstrated that the ViBa can generally enhance the behaviour of NC structures under earthquake motions. It is important to note that the efficiency of ViBa is dependent on multiple factors such as the tuning conditions (i.e., different earthquakes require different tuning), earthquake magnitude and frequency content, and soil type. Results discussed here show that increasing the ViBa-structure mass ratio is not always a good strategy to improve the performance of the ViBa. Thus, it is essential that more studies with much larger sample sizes are carried out to accurately establish a relationship between mass ratio, ViBa and other factors over a variety of ground motions.

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