COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

3D BASE ISOLATION OF BUILDINGS

Marco Domaneschi[1], Gian Paolo Cimellaro[2]

[1] Politecnico di Torino DISEG
marco.domaneschi@polito.it

[1] Politecnico di Torino DISEG
gianpaolo.cimellaro@polito.it

Abstract

A 3-D base isolation system to control the structural effects of both the horizontal and vertical components of ground motion has been recently presented in literature and it is herein briefly summarized. A building model is used to test the 3D base isolation arrangement that consists of elastomeric bearings acting both in the horizontal and vertical directions, and an innovative negative stiffness devices acting only in the vertical direction. The elastomeric bearings horizontal reaction force is reproduced through the implementation of a linearized approach. The negative stiffness device in the vertical direction can be considered as an adaptive passive protection system, which can apparently change the stiffness of the structure.

Numerical analyses show that the presence of the negative stiffness devices in the vertical direction coupled with the elastomeric bearings reduces both the vertical and the horizontal absolute acceleration in the structure. Nevertheless, accordingly with the passive control theory, the relative displacements increase. The adoption of supplemental damping from the implementation of high damping rubber bearings allows to mitigate such amplification effects without introducing specific dampers.

Keywords: 3D base isolation, vertical mitigation, three dimensional ground motion, building, numerical simulation, nonlinear behavior.

1 INTRODUCTION

From decades seismic base isolation focuses the attention of the structural engineering community. Indeed, it plays a special role in mitigating the seismic effect on structures. Base isolators turn out to be able (i) to shift the main structural natural frequencies away from the most dangerous seismic frequencies; (ii) to act as an internal fuse for the interaction forces; (iii) to dissipate part of the introduced energy; (iv) to supply additional damping. Therefore, it is widely accepted (and standardized) that base isolation gives the best architectural impact (being almost invisible) and has a better seismic performance among the other structural protection techniques.

Despite it has long been assumed that the effect of the vertical component of the earthquakes could be ignored for seismic reliability of structures, it has been demonstrated how the effect of the vertical component should be considered along with the horizontal one.

This paper is focused on a mechanical arrangement [1] able to reduce of the structural and non-structural dynamic effects associated to the vertical component of the ground shaking. When coupled with traditional horizontal base isolation devices, the proposed solution overcomes the present limitation of standard base isolation systems that exclusively mitigate the horizontal seismic forces. The concept negative stiffness is implemented in the vertical direction to provide effective vertical vibrations absorption in constrained bistable structures.

2 LITERATURE REVIEW

A common perception among the professional engineers is still that the vertical component of the ground motion is lower than the horizontal component, thereby V/H ratio (ratio of vertical to horizontal peak ground acceleration) is assumed to remain less than unity. Many codes worldwide [2,3] still suggest the use of a spectral shape for the vertical component derived from the horizontal component, using an average V/H ratio (e.g. 2/3), as originally proposed by Newmark et al. [4]. As a result, all components of motion have also the same frequency content. The frequency content, however, is demonstrably different and the fixed ratio rule for V/H is unconservative in the near-field and over-conservative at large distances from the epicenter [5]. The V/H ratio was confirmed to be > 1.0 within a 5 km radius of the earthquake source, > 2/3 within 25 km radius and dependent on earthquake magnitude. Table 1 below shows some events and stations close to the fault with significant V/H ratio.

Event	**Station (Mw)**	**H1(g)**	**H2(g)**	**V(g)**	**V/H**	**Distance***
Gazli, USSR 1976	Karakyr (6.8)	0.61	0.72	1.26	1.76	5.5 km
Imperial Valley 06 1979	El Centro Array #6	0.41	0.44	1.6	3.77	1.4 km
Kobe, Japan 1995	Port Island (6.9)	0.31	0.28	0.56	1.79	3.3 km
Loma-Prieta, USA 1989	LGPC (6.9)	0.56	0.61	0.89	1.47	3.9 km
Nahanni, Canada 1985	Site 1 (6.8)	0.98	1.1	2.09	1.9	9.6 km
Northridge-01 1994	Rinaldi (6.7)	0.84	0.47	0.85	1.02	6.5 km
Palm Springs 1986	Cabazon (6.1)	0.22	0.21	0.36	1.67	7.8 km

* Closest distance to fault

Table 1: Events and stations close to the fault with significant V/H ratio.

Therefore, despite it has long been assumed that the consideration of the effect of the horizontal component of earthquakes suffices for seismic reliability of structures, it has been shown in many cases (e.g. near-field strong ground motion) that the vertical component should be consistently considered along with the horizontal one. This issue becomes a great concern for conventional seismic isolation system that are able to reduces the structural effects of the horizontal component of an earthquake, while the vertical component is transmitted directly into the structure. As such, there is considerable and increasing research interest worldwide in vertical and three-dimensional (3D) isolation systems to protect a wide range of structures and valuable facilities such as heritage assets and specialized equipment. Indeed, they are not only unique and expensive, but also critical to safe operation [6-9].

Current standard EN 1998-1 [10] cover the design of seismically isolated structures in which the isolation system, below the main mass of the structure, aims at reducing the seismic response of the lateral-force resisting system. Again, EN 15129 [11] specifies that isolators provide isolation against only horizontal seismic actions.

Structural base isolation against vertical vibrations in parallel with standard horizontal base isolation remains a challenge in both research and practice.

Some attempts of 3D base isolation systems can be found in literature. A 3D isolation system has been introduced in 1990 [12] and it consists of helical steel springs that are flexible horizontally and vertically. The spring is essentially undamped so it needs to be used in conjunction with supplemental dampers. The system has been applied in two buildings in California. Limitations can be identified in the coupling between the horizontal and the vertical motion due to geometric nonlinearities. Similarly, 3-D seismic isolation devices that employ laminated rubber bearings for the horizontal direction and helical springs or seal type air springs in the vertical direction are also studied [13-16,9]. The issue of concern for these solutions is the pitching and rolling effects, so an additional rocking suppression system should be also provided.

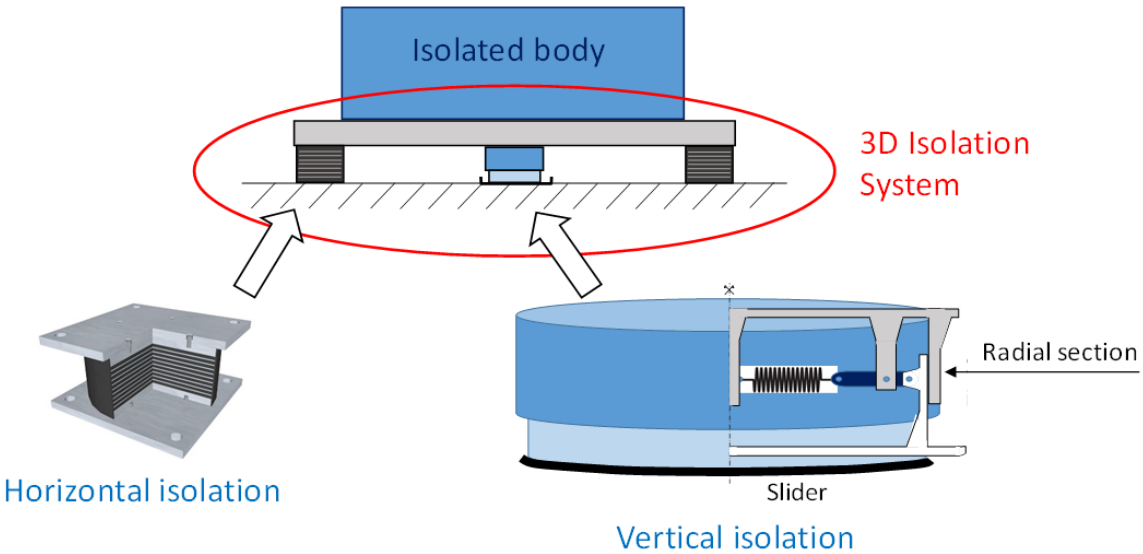


Figure 1: 3D isolation system.

This paper deals with the challenge of how realize a 3D base isolation system for protecting a wide range of structures and valuable assets.

A weakening vertical behavior simulates the yielding of the global system without changing the real stiffness of the structure. It allows moving the structural response away from dangerous amplification. Therefore, the mechanism decouples the vertical ground shaking from the superstructure, generating the vertical base isolation. In the same way that standard isolators decouple the horizontal component of the ground motion (Figure 1).

The mechanism that allows to isolate the superstructure from the vertical component of the earthquake consists in a mechanical assembly of passive components (i.e. springs, rods, pivots). The concept of negative stiffness [17] drives the concept. Vibration control can be carried out by modifying the self-stress level of the structure in order to shift the natural frequencies away from excitation [18]. Recent research has shown that constrained bistable structures can provide effective horizontal vibrations absorption capacity [19,20].

3 PROPOSED NEGATIVE STIFFNESS DEVICE

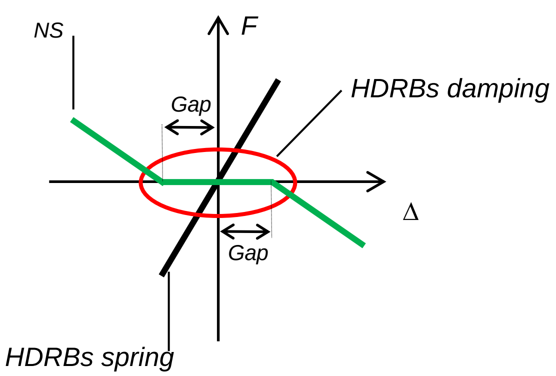
Figure 1 reports the general scheme as "radial section" of the proposed negative stiffness device to isolate the superstructure from the vertical components of the earthquake motion. More details can be found in [1].

The horizontal prestressed spring remains at rest until the vibrations induced by the vertical component of the earthquake change the alignment between the lever and the spring. Then the vertical component of the prestressed spring force generates a bending moment, on the left and around the pivot, which is in balance with the moment to the right of the pivot. Being the arm to the right of the pivot smaller than that one on the left, the force acting on the superstructure will be greater than the vertical component of the prestressed spring force. In this way the reduction of the vertical rigidity of the system (weakening) is generated, which has the effect of amplifying the displacement induced by the vertical component of the earthquake. This mechanism decouples the vertical ground shaking from the superstructure, generating the vertical base isolation. Preliminary results highlight how the vertical isolation mechanism is effective in reducing the vertical acceleration of the superstructure and promising for further development and implementations on a wide range of structures.

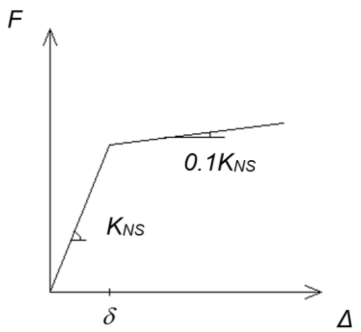
The mechanism for vertical base isolation adopts consolidated mechanical solutions. Differently from current approaches [13-16,9] that are based on linear elastic springs (helical and air spring), it is able to show a nonlinear weakening behavior that is essential for limiting the external forces that could be transmitted directly to the superstructure.

4 METHODOLOGY

The isolation mechanism should be able to generate a force that pushes the isolated structure in the same direction of the seismic induced relative displacement between the base and the ground (not in the opposite as in the case of positive stiffness). It simulates an apparent weakening without changing the real stiffness of the structure, in order to move the system appropriately far from the resonance condition. In other words, a pseudo yielding is created, that is below the real yielding of the superstructure.



(a)



(b)

Figure 2: (a) charactersitics of the negative stiffness device. (b) Force-displacement laws of the isolation mechanism.

The displacement level at which the pseudo yield occur (called Gap) can be fixed so that the negative stiffness (NS) transfers almost zero forces to the structure until the displacement is smaller than the Gap. Assuming a linear stiffness for the HDRBs and considering their inherent damping, the assembly is described by the following schemes.

When the displacement is within the Gap, the negative stiffness mechanism is not activated. When the Gap threshold is overcome, the negative stiffness component is transferred to the structure (Figure 2a). Actually, the apparent reduction of stiffness produces an increment of displacement that could be necessary to be controlled. Therefore, a small amount of damping could be needed and it can be provided by the HDRBs.

A further positive characteristic of the assembly is that it is able to re-center when the external forces are removed. Therefore, residual deformations at the base isolation level are restored, unless the main structure itself developed plastic deformations due to yielding. More details on the proposed negative stiffness device can be found in [1].

5 APPLICATION

The effectiveness of the proposed concept for the mitigation of the vertical vibrations is now assessed using a simple structure. It consists in a 2-D frame not related to a specific application, with two columns, a rigid horizontal beam and a rigid horizontal base floor [1]. It has the following characteristics: span L = 9.15 m and height h = 3.96 m, distributed mass on the beam and base floor m = 160000 kg (each one), frame's total horizontal stiffness K_H = 77000 kN/m for a corresponding vibration period T_H = 0.28 s, frame's total vertical stiffness K_V = 5.7×106 kN/m for a corresponding vertical period of T_V = 0.033 s, assumed damping ratio ξ=5% through Rayleigh damping matrix. T, N, M are the internal forces in the columns: respectively shear force, axial force, bending moment. E is the Young modulus, A and I are the cross section area and inertia modulus of the columns respectively. x_i, y_i, θ_i are the Lagrangian coordinates, x_g, y_g the ground motion displacements components in the horizontal and the vertical direction respectively. The rocking motion is now disregarded at the isolation level. At the end, five degrees of freedom are considered in the structure.

Each isolator is assumed with linear elastic behavior and has a fixed damping ratio of 15%. This value is typical for high damping rubber bearings, or lead rubber bearings, at larger cycles of hysteresis [7]. Two configurations are considered: (i) isolated structure without the vertical isolation mechanism and (ii) the complete 3D isolation.

The structure in the second configuration is arranged with the vertical isolation mechanism uncoupled from the horizontal one (rubber bearings). Thus, it acts in the vertical direction only and provides no force in the horizontal direction. Hence, in the horizontal direction the rubber bearings ensure the base isolation, while the total vertical Force-Displacement law at the isolator level is the sum of both the NS and the HDRBs contributions as they act in parallel.

The vertical isolation mechanism is designed to get a specific Force-Displacement law as depicted in Figure 2b. It is nonlinear elastic and the parameters that characterize the behavior are the following:

- The stiffness of the first branch, equal to the total vertical isolators stiffness K_{NS}.
- The stiffness of the second branch, equal to 10% of K_{NS}.
- The gap-displacement δ when the NS is engaged.

Focusing on the rubber bearings devices, assuming a starting range of horizontal stiffness for the isolators, the goal is to find the stiffness at which the vertical isolation mechanism is more efficient in mitigating the vertical acceleration of the superstructure. The first assumption is to consider a stiffness range that correspond to a horizontal period of vibration between 1 s and 4 s. Then, for identifying the total vertical stiffness of the isolators, the assumption is to have a ratio between the vertical and the horizontal reactions equal to 1000 (representative of the most of the rubber devices available on the market).

For the selection of the optimal vertical stiffness, tests are performed in the vertical direction using a suite of ten earthquake records with high vertical components of ground motion. For each record, and for each stiffness, a range of values of gap-displacement δ are assumed. Following the first-step analyses, the value δ = 1mm results satisfactory in terms of vertical acceleration mitigation. Therefore, for the aim of this preliminary study, this value is adopted. The second step of the analysis concerns the design of the rubber isolators. After the selection of the optimal vertical stiffness, the purpose is to design an isolation system that is able to withstand the displacements and the stresses induced by the seismic loading. The design must take in to account some requirements and verifications that appear in most codes (e.g. [21]).

Next Figure 3 shows the comparison of the mean values and standard deviations of the maximum vertical accelerations, for traditional base isolation vs 3D base isolation and for different vertical stiffnesses, of all the ground motions considered. A transition zone in the mean values is observed where the behavior of the two isolation typologies is equivalent. This is due to the relative displacements are smaller. Hence the vertical isolation mechanism is engaged only few times. Instead, when the stiffness is small, a significant reduction of accelerations is obtained. Nevertheless, tensile displacements are also highlighted at the lowest stiffness values.

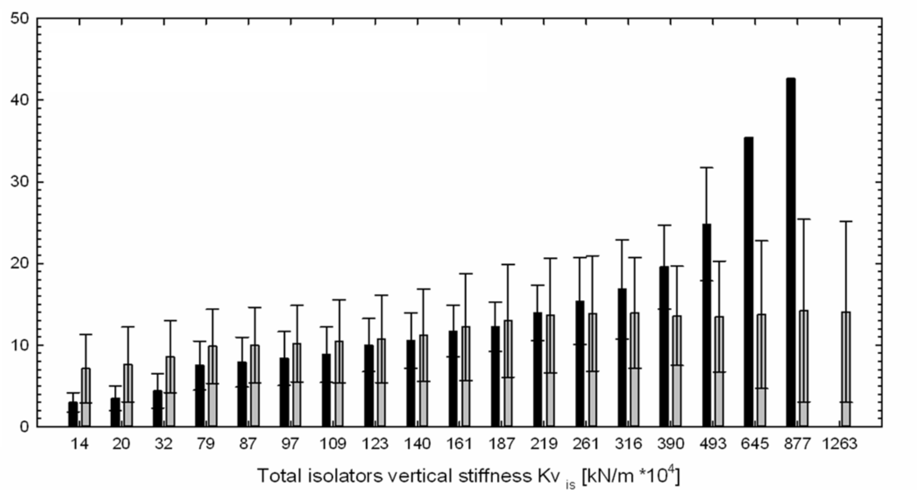


Figure 3: comparison of the mean values and standard deviations of the maximum vertical accelerations in the isolated system, for traditional base isolation (grey bars) vs 3D base isolation and for different vertical stiffnesses (black bars).

6 CONCLUSIONS

- The paper deals with an innovative solution from literature that consists in the implementation of negative stiffness devices in parallel with traditional rubber bearings in a base isolated building to mitigate the vertical response. Therefore, a 3-D base isolation with uncoupled reaction components is achieved.
- To test the proposed procedure with respect to traditional isolated ones, a simple SDOF case study is considered. The results show that the implementation of negative stiffness devices in the vertical direction reduces the vertical accelerations. However, consistently with the base isolation theory, there are increments of displacements at the isolator level.

Thus, the implementation of additional damping at the isolation level is advisable to limit relative displacements.

- Internal forces in the vertical mitigation device are 2-3 times larger than the structural weight. Therefore, the design concept may result difficult to be implemented in practical applications and likely restricted to special conditions (light highly sensitive equipment or sculptures and artistic masterworks).
- Next research will be focused on the development of a prototype to evaluate the practicability and the effectiveness of the proposed solution.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n°ERC_IDEalreSCUE_637842 of the project IDEAL RESCUE - Integrated DEsign and control of Sustainable CommUnities during Emergencies.

REFERENCES

[1] G.P. Cimellaro, M. Domaneschi, G. Warn, Three-Dimensional base isolation using vertical negative stiffness devices. *Journal of Earthquake Engineering*. Published online: 10 Aug 2018. DOI: 10.1080/13632469.2018.1493004

[2] NEHRP 1994, Recommended provisions for seismic regulations for new buildings. Federal Emergency Management Agency - FEMA 222A, Washington DC, USA.

[3] UBC 1997, The Uniform Building Code. International Conference of Building Officials, Whitiier, California, USA.

[4] N.M. Newmark, J.A. Blume, K.K. Kapur, "Seismic Design Spectra for Nuclear Power Plants. *Journal of the Power Division, Proceedings of ASCE*, **99**, 287–303, 1973.

[5] C.J. Collier and A.S. Elnashai, A Procedure for Combining Vertical and Horizontal Seismic Action Effects. *Journal of Earthquake Engineering*, **5**(4), 521-539, 2001.

[6] B. Basu, O. Bursi, F. Casciati, S. Casciati, A. Del Grosso, M. Domaneschi, L. Faravelli, J. Holnicki, H. Irschik, M. Krommer, M. Lepidi, A. Martelli, B. Oztork, F. Pozo, G. Pujol, Z. Rakicevic, J. Rodellar, An EACS joint perspective. Recent studies in civil structural control across Europe. *Structural Control & Health Monitoring*, **21**(12), 1414–1436, 2014.

[7] F. Perotti, M. Domaneschi, S. De Grandis, The numerical computation of seismic fragility of base-isolated NPP buildings. *Nuclear Engineering and Design*, **262**, 189–200, 2013.

[8] H. Abdollahiparsa, P. Homami, F. Khoshnoudian, Effect of Vertical Component of an Earthquake on Steel Frames Considering Soil-Structure Interaction. *SCE Journal of Civil Engineering*, **20**(7), 2790-2801, 2016.

[9] Z. Zhou, J. Wong, S. Mahin, Potentiality of Using Vertical and Three-Dimensional Isolation Systems in Nuclear Structures. *Nuclear Engineering and Technology*, **48**, 1237-1251, 2016.

[10] EN 1998-1, European Standard, Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, 2003.

[11] EN 15129, European Standard, Anti-seismic devices, 2009.

[12] J.M. Kelly, E. Quiroz, Testing and Evaluation of CEGB Isolation System. University of California, Berkeley, CA, 1990.

[13] J. Suhara, T. Tamura, K. Ohta, Y. Okada, S. Moro, Research on 3D base isolation system applied to new power reactor 3D seismic isolation device with rolling seal type air spring: Part 1. *Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17)*, Prague, Czech Republic, August 17 –22, 2003.

[14] K. Inoue, M. Fushimi, S. Moro, M. Morishita, S. Kitamura, T. Fujita, Development of Three-Dimensional Seismic Isolation System for Next Generation Nuclear Power Plant. *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, 2004.

[15] M. Morishita, K. Inoue, T. Fujita, Development Of Three-Dimensional Seismic Isolation Systems For Fast Reactor Application. *Journal of Japan Association for Earthquake Engineering*, **4**(3), 6, 2004.

[16] S. Kitayama, D., Lee, M.C. Constantinou, L., Kempner, Probabilistic seismic assessment of seismically isolated electrical transformers considering vertical isolation and vertical ground motion. *Engineering Structures*, **152**, 888-900, 2017.

[17] W.G. Molyneaux, Supports for vibration isolation. A.R.C. - C.P. No.322, Aeronautical Research Council, 1957.

[18] N. Bel Hadj Ali and I.F.C. Smith, Dynamic behavior and vibration control of a tensegrity structure. *International Journal of Solids and Structures*, **47**, 1285–1296, 2010.

[19] D.T.R. Pasala, A.A. Sarlis, A.M., Reinhorn, S. Nagarajaiah, M.C. Constantinou, D. Taylor, Apparent Weakening in SDOF Yielding Structures Using a Negative Stiffness Device: Experimental and Analytical Study. *J Struct Eng ASCE* , **141**(4), 2015.

[20] A.A. Sarlis, D.T.R. Pasala, M.C. Constantinou, A.M. Reinhorn, S. Nagarajaiah, D. Taylor, Negative Stiffness Device for Seismic Protection of Structures: Shake Table Testing of a Seismically Isolated Structure. *J Struct Eng*, **142**(5), 2016.

[21] AASHTO, Guide specifications for seismic isolation design, 3rd Edition. Washington, DC, 2010.