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EFFECTS OF VERTICAL SEISMIC COMPONENT ON BASE ISOLATION SYSTEMS: THE CASE STUDY OF CASTELLUCCIO DI NORCIA

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Abstract

Seismic isolation mitigates earthquake-induced forces by increasing structural natural vibration period and damping effects. While traditional isolation systems primarily address horizontal ground motions, the vertical component is often neglected unless required by regulations. However, in near-fault regions, vertical ground motions can be more intense than horizontal ones, potentially affecting isolated structures. This study examines the impact of vertical seismic components on seismically isolated structures in near-fault zones, focusing on the reconstruction of Castelluccio di Norcia, a historic village devastated by the 2016 Central Italy earthquake. The reconstruction uses an "isolated artificial ground" approach, where buildings are supported on a stepped reinforced concrete plate with Concave Curved Surface Sliders. A Finite Element Model (FEM) was developed to analyze the dynamic response under various earthquakes using time-history analyses. Results show that vertical seismic components have a minimal impact on horizontal displacements but cause significant fluctuations in shear forces due to variations in axial loads. These findings enhance understanding of vertical seismic actions in near-fault scenarios and their implications for isolation design.

Keywords: Near-field Earthquake, Vertical Component of Ground Motion, Seismic Isolation, Reconstruction Project of Castelluccio di Norcia

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1 INTRODUCTION

Seismic isolation is now a well-established and widely used technique for both the construction of new structures and the reconstruction or restoration of buildings damaged or destroyed by earthquakes. Isolation systems, which allow for significant horizontal displacements, effectively reduce accelerations induced by ground motion. This is achieved through an increase in the structural natural vibration periods and the damping effects provided by the isolation system itself. As for the vertical direction, traditional seismic isolation devices behave similarly to simple supports. In practical terms, the structural response in this direction remains comparable to that of a fixed-base structure. According to Italian regulations, the vertical component of an earthquake must be considered only when the construction site experiences ground accelerations exceeding 0.15g and includes specific structural elements, such as: horizontal elements with spans greater than 20 meters, prestressed elements (excluding slabs with spans less than 8 meters), cantilever elements with spans exceeding 4 meters, thrust-type structures, beams supporting columns, buildings with suspended floors, bridges, and structures with isolation systems where the ratio of vertical stiffness to equivalent horizontal stiffness is less than 800. In these cases, the vertical component must be considered if vertical vibration modes significantly excite the structure mass, otherwise it can be neglected. However, this rule is not always held in near-fault regions, where the vertical seismic component can be comparable or even larger than the horizontal one. In such areas, ground shaking is influenced by several factors related to fault type and rupture mechanisms, which are generally absent at medium and long fault distances. Numerous studies on these phenomena [2, 3, 4, 5] have shown that ground motions are significantly more intense in near-fault zones, with the vertical component sometimes exceeding twice the intensity of the horizontal ones [6, 7].

Despite this, very few regulations currently provide detailed guidance on defining seismic actions for near-fault zones [8] as well as design and verification rules of structures. In most standards, in fact, design procedures remain the same as those for medium and far-fault sites, relying primarily on code-prescribed site spectra.

This paper examines the impact of the vertical component of earthquakes on the behavior of seismically isolated structures in near fault zones. Specifically, it focuses on the reconstruction project of Castelluccio di Norcia, which serves as a case study since it is close to an active fault (that produced in 2016 the earthquake of magnitude Mw=6.5). The project involves rebuilding part of the historic center, destroyed during the 2016 earthquake sequence in Central Italy, using an "isolated artificial ground" approach, where buildings are reconstructed on a stepped plate that behaves as a common foundation isolated by Concave Curved Surface Sliders (CCSSs). To analyze the dynamic behavior of the structure, a Finite Element Model (FEM) was developed and nonlinear time-history analyses were conducted, using acceleration time-histories as seismic input, selected in accordance with NTC18.

2 CASE STUDY AND MODELLING

Following the seismic events in Central Italy in 2016, particularly the October 30th earthquake, the village of Castelluccio di Norcia suffered extensive damage and structural collapses. As part of the reconstruction effort, a reinforced concrete plate supported by CCSSs isolation devices will be constructed in the area of the historic center that experienced the most significant destruction. This plate will serve as a common foundation, providing seismic isolation for all the buildings rebuilt above it [9]. Given Castelluccio di Norcia's iconic status and its importance as a tourist destination, preserving the village pre-earthquake layout is a key objective. To achieve this, the isolated plate is designed with a series of stepped levels, ensuring that the village original skyline remains unchanged (Figure 1).

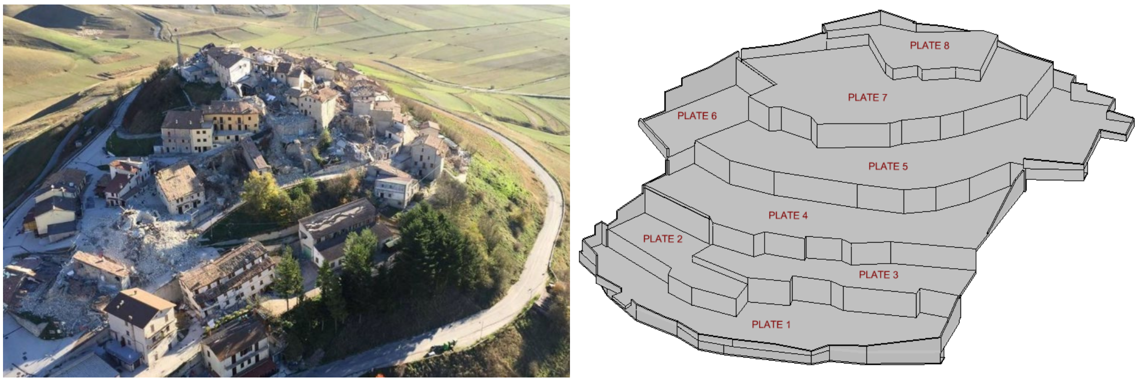

Figure 1: Castelluccio di Norcia after the 30/10/2016 seismic event *(left)*; Stepped plate used for the reconstruction project of Castelluccio di Norcia *(right)*.

The FEM model for the intervention was developed using shell elements for the stepped plate and nonlinear links for the friction pendulum devices. The isolators have a curvature radius of 3 meters and a friction coefficient of 3.5%. To limit the axial load on the isolators, they were arranged in a 5 m × 5 m grid. The shell features an irregular mesh that approximately follows the distribution of the isolators; a more refined mesh was not adopted at this stage in order to reduce the computational effort. To account for the dynamic interaction between the plate and the underlying aggregates, the latter were modeled in a simplified manner using multi-degree-of-freedom oscillators composed of frame elements. The MDOF oscillators are calibrated in order to well approximate the effects of the real buildings on the plate, in terms of base shear and overturning moment. Figure 2 shows a pictorial view of the developed numerical model, while Table 1 reports the fundamental period of vibration of both the plate and the buildings.

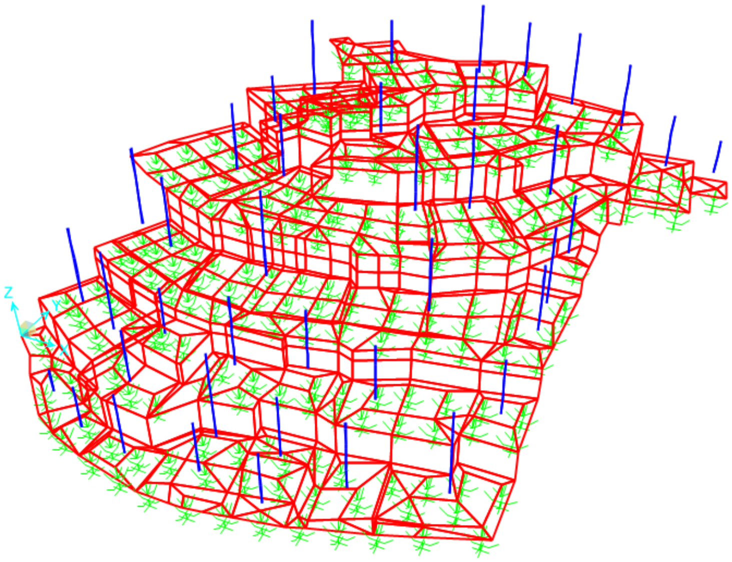

Figure 2: FEM model of the reconstruction project of Castelluccio di Norcia.

Isolation period (T_{iso})	Range of horizontal periods of buildings (T_{horiz})	Range of vertical periods of buildings (T_{vert})
3.31 s	0.2 ÷ 0.01 s	0.05 ÷ 0.01 s

Table 1: Fundamental periods of the stepped plate.

3 DEFINITION OF THE SEISMIC INPUT

Time history analyses enable the integration of the equations of motion using a time history of accelerations as input, accounting for the linear or nonlinear dynamic behavior of the structural systems. Most seismic design standards worldwide permit the use of artificial, simulated, or natural time histories, provided they are compatible with the elastic spectrum of the construction site. Specifically, the Italian code requires the use of at least seven accelerograms, ensuring that their average SRSS (Square Root of the Sum of Squares) spectrum aligns with the site spectrum, amplified by a coefficient α, typically set to 1.3 and never exceeding $\sqrt{2}$. The average SRSS spectrum is derived by averaging the SRSS spectra computed for each pair of horizontal time histories. Within the relevant period range, this spectrum must remain within +30% to -10% of the amplified code site spectrum. If this condition is not met, linear amplitude scaling of the accelerograms is permitted. For the case study at hand, the selection of the accelerograms representative of the horizontal components of the seismic action was conducted using the RexelWeb search tool, ensuring compatibility with the horizontal elastic spectrum at the Collapse Limit State (CLS) as defined by NTC18 for the Castelluccio di Norcia site. Regarding the vertical seismic action, the compatibility of the vertical components of the selected events was verified a posteriori, since the search tool does not permit to impose compatibility with the vertical spectrum too. Table 2 reports data of the selected records while Figure 3 shows spectra of the individual unscaled components. Moreover, it is worth noting that the adopted selection tool does not define spectrum compatibility on the basis of the average SRSS spectrum, and assumes the arithmetic mean of the fourteen horizontal records to check the code compatibility in terms of pseudo-acceleration response spectrum. Consequently, the identified records were manually divided into two orthogonal directions and scaled. During this process, scale factors were chosen to minimize the gap between the SRSS spectra and the site spectrum.

Figure 4 shows the spectra obtained after the scaling, while Table 3 reports the scaling factors adopted for the two components of the seismic events.

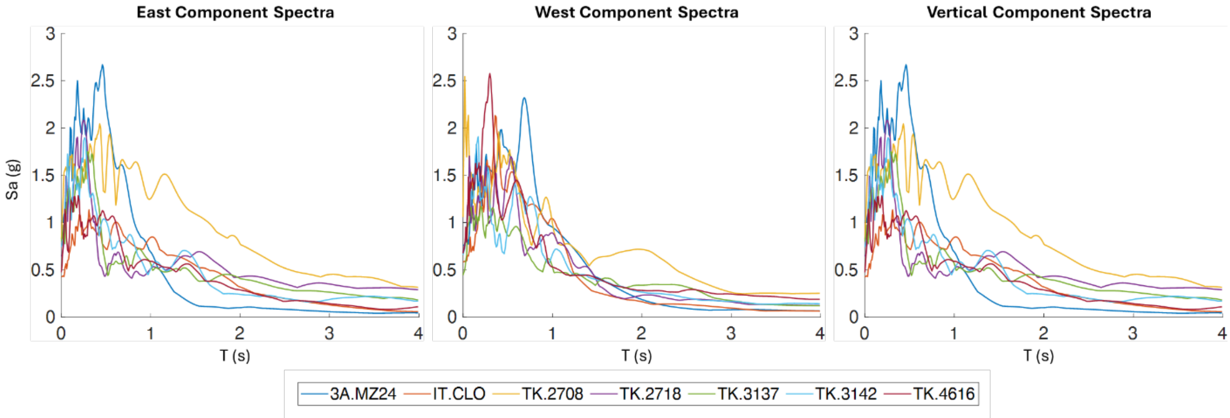

Figure 3: Spectra of the individual unscaled component.

Load Case	Network	Station Code	Date	Magnitude (Mw)
TH1	3A	MZ24	30/10/2016	6.6
TH2	IT	CLO	30/10/2016	6.6
TH3	TK	2708	6/2/2023	7.7
TH4	TK	2718	6/2/2023	7.7
TH5	TK	3137	6/2/2023	7.7
TH6	TK	3142	6/2/2023	7.7
TH7	TK	4616	6/2/2023	7.7

Table 2: Load cases used in direct integration analyses.

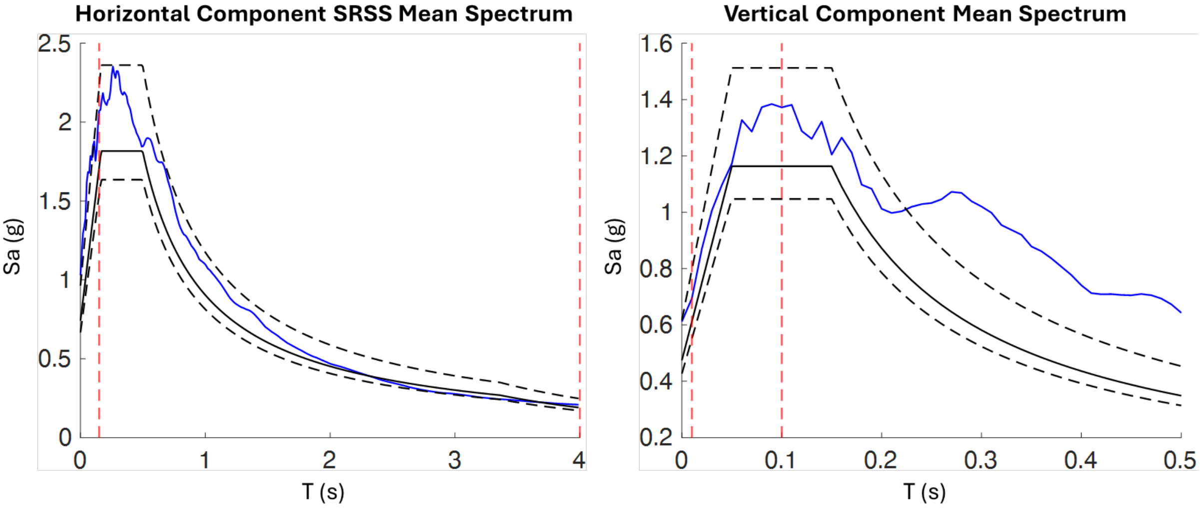

Figure 4: Scaled average spectra of horizontal (SRSS) and vertical component.

Load Case	Scale Factor (Horizontal)	Scale Factor (Vertical)
TH1	1.4	2.31
TH2	1.1	0.77
TH3	0.7	0.93
TH4	0.8	1.01
TH5	1.3	1.3
TH6	0.7	1.3
TH7	1.3	1.57

Table 3: Scale factors used to obtain compatibility with the code spectrum for horizontal and vertical component.

As can be observed from Figure 4, the adopted scaling factors ensure the compatibility of the average spectrum with the site spectrum over the entire range of significant periods. For the horizontal component, considering the code indications, the period range 0.15 s - 1.2T_{iso} is assumed for the compatibility check. As for the vertical component, standards do not define specific ranges over which the spectrum compatibility has to be assured; therefore, the range of periods (from 0.01 s to 0.1 s) is chosen considering the overall vertical vibration periods of the structural system (isolation system and buildings) and the relevant participating mass ratios.

4 RESULTS OF DIRECT INTEGRATION ANALYSES

The following section summarizes the horizontal displacements obtained from the direct integration analyses, both with and without the vertical earthquake component. For the analyses including the vertical actions, Table 4 shows, for each seismic event, the maximum values of the displacement of the isolators placed approximately at the four vertices of the plate; the latter are obtained taking into account the vectorial combination of the displacements occurring at each time step in the two main orthogonal directions. The mean value for each device is obtained by averaging the maximum displacements obtained for each event. Table 5 shows the corresponding displacements obtained from the analysis that disregards the vertical actions.

Load Case	Displacements of Isolator n° 1 (m)	Displacements of Isolator n° 4 (m)	Displacements of Isolator n° 62 (m)	Displacements of Isolator n° 197 (m)
TH1	0.274	0.276	0.275	0.275
TH2	0.315	0.313	0.314	0.314
TH3	0.595	0.586	0.588	0.591
TH4	0.436	0.433	0.430	0.440
TH5	0.653	0.649	0.649	0.653
TH6	0.154	0.153	0.154	0.154
TH7	0.667	0.669	0.668	0.668
Mean	**0.442**	**0.440**	**0.440**	**0.442**

Table 4: Resultant displacements obtained with vertical component for the selected devices.

Load Case	Displacements of Isolator n° 1 (m)	Displacements of Isolator n° 4 (m)	Displacements of Isolator n° 62 (m)	Displacements of Isolator n° 197 (m)
TH1	0.280	0.280	0.280	0.279
TH2	0.321	0.320	0.320	0.320
TH3	0.600	0.591	0.593	0.596
TH4	0.452	0.449	0.446	0.456
TH5	0.628	0.625	0.625	0.628
TH6	0.152	0.150	0.151	0.151
TH7	0.649	0.651	0.650	0.650
Mean	**0.440**	**0.438**	**0.438**	**0.440**

Table 5: Resultant displacements obtained without vertical component for the selected devices.

In both cases, the displacements are almost equal for all the isolators. It can be deduced that the plate behaves as a horizontally rigid element with almost null torsional effects and absence of relative movements between the supports. In some load cases (TH1, TH2, TH3, TH4), the horizontal displacements obtained considering the vertical accelerations of the earthquake are smaller than in the case where the vertical component is not considered, while in other cases (TH5, TH6, TH7), the opposite occurs. However, these differences are very small, and globally, an identical mean horizontal displacement is obtained whether the vertical earthquake component is considered or not.

Figure 5 and Figure 6 show the force-displacement cycles, in both the X and Y directions, of an isolator subjected to TH2, TH3 and TH5, considering or not the vertical component, respectively.

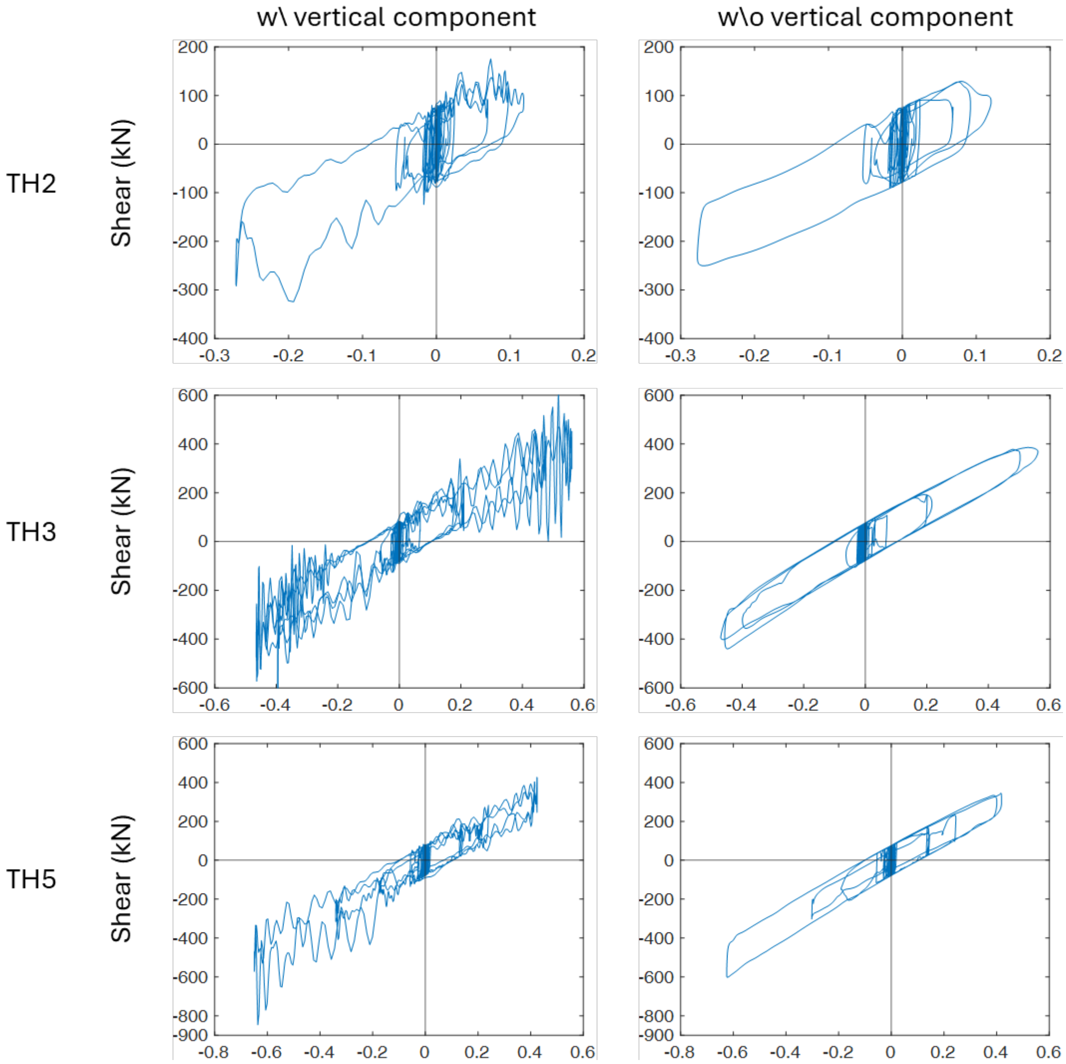

Figure 5: Force-Displacement cycles obtained with and without the vertical component in X direction.

As can be observed from the hysteretic cycles, displacements are not particularly affected by the presence of the vertical component, while the shear forces are affected more. In particular, the vertical component of the earthquake causes instantaneous increases and decreases in the shear forces on the devices, as a consequence of the inertia vertical forces acting on the devices, resulting in an increase or decrease of the friction forces during the horizontal motion.

Finally, a graph summarizing the axial loads ratios on the devices is shown in Figure 7. The graph compares the ratios between axial loads obtained from THs (mean values) and vertical loads at seismic condition (VSC), and axial loads obtained from the static ultimate limit state combination (ULS) and vertical loads at seismic condition.

Observing the ratios of each device, it can be seen that for most isolators, the TH/VCS ratios are always greater than the ULS/VCS ratios. In particular, the vertical component of the earthquake doubles the vertical loads at seismic conditions. Ultimately, the axial loads produced by vertical earthquakes can significantly influence the design of isolation devices.

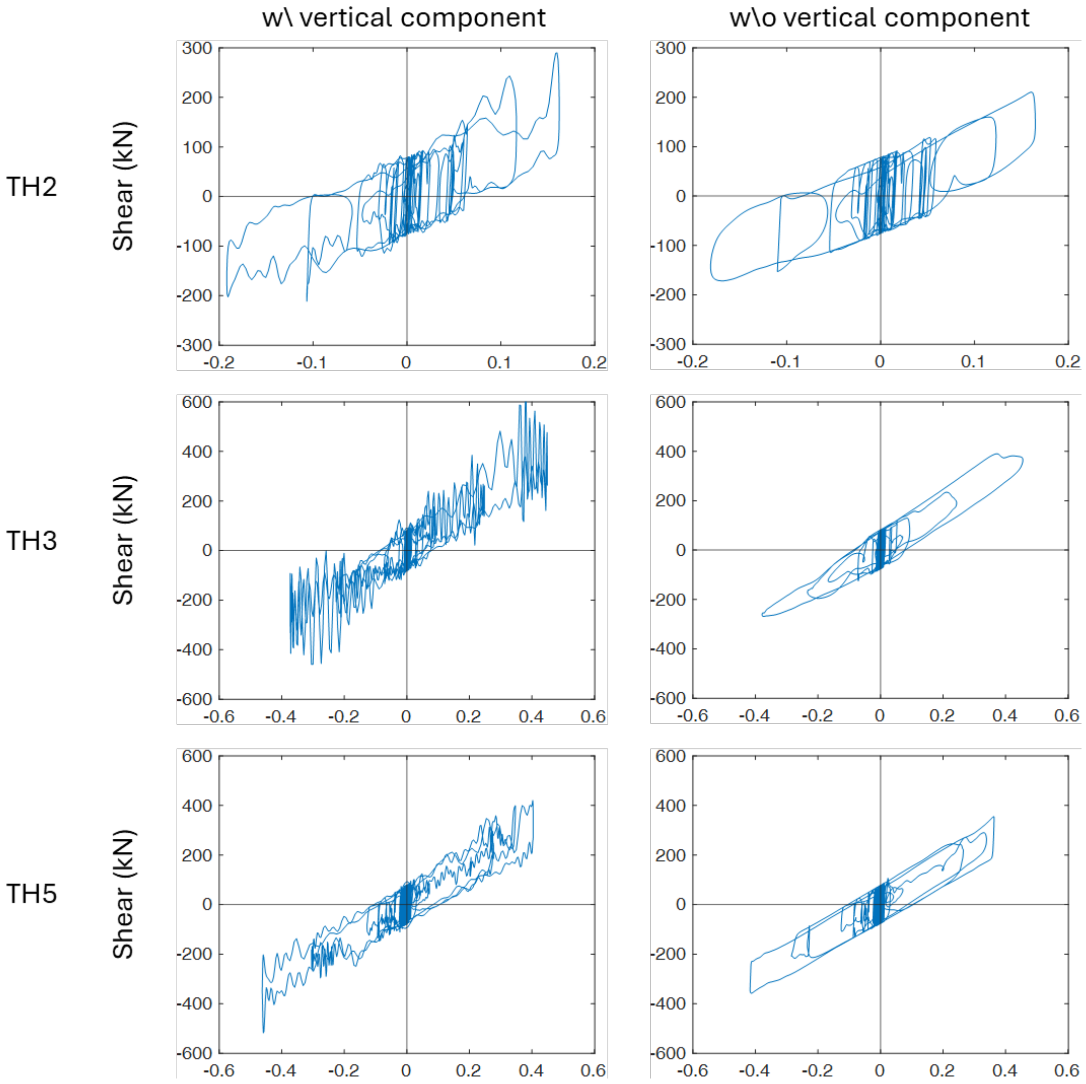

Figure 6: Force-Displacement cycles obtained with and without the vertical component in Y direction.

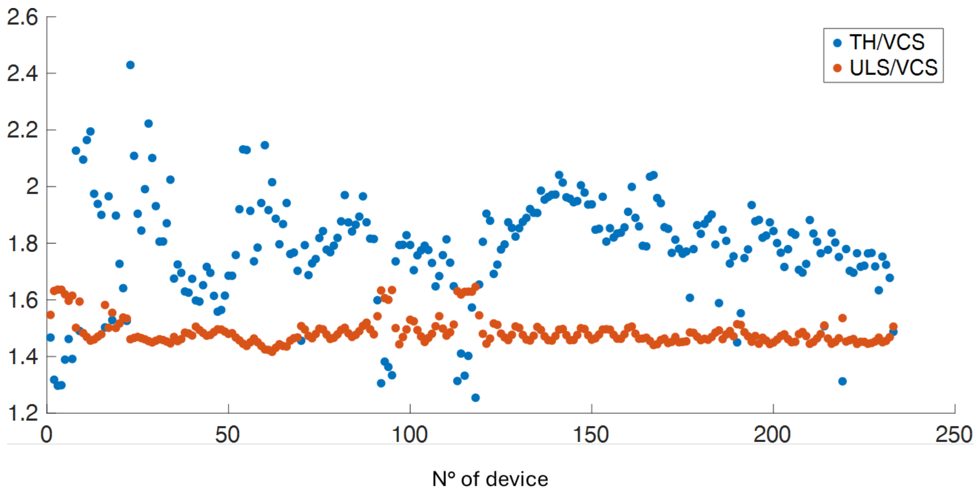

Figure 7: Comparison between axial loads obtained for the direct integration analyses, static condition for earthquake combination and ULS combination.

5 CONCLUSIONS

This study examined the effects of the vertical component of earthquakes on the behavior of a seismically isolated structure in a near-fault area, using the Castelluccio di Norcia reconstruction project as a case study. The structural response was analyzed through Finite Element modeling and time-history analyses, incorporating site-specific seismic input selected in accordance with NTC18.

The main fundings of the study can be summarized as follows:

- The comparison of results with and without the vertical earthquake component revealed negligible differences in terms of horizontal displacements of the isolators.
- While displacements remained largely unaffected, the vertical component introduces fluctuations in shear forces due to variations in axial loads on the isolators. These fluctuations, caused by vertical inertia forces, led to instantaneous variations of the friction force within the isolation devices.
- The analysis of axial loads showed that earthquake-induced vertical forces altered the load distribution on the isolators. However, these variations remained within the expected range when compared to static earthquake load combinations and the ultimate limit state (ULS) conditions.

Overall, the study confirms that while the vertical component of seismic action may not significantly alter horizontal displacements in seismically isolated structures, it does affect force distributions within the isolators and thus should be considered in the design. These findings underscore the need for further research and potential refinement in seismic regulations, particularly for near-fault conditions where vertical accelerations can be substantial.

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