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Design of a base-isolated artificial ground accounting for 3D seismic input: the case study of Castelluccio di Norcia

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Abstract

Seismic isolation is a technique that reduces the impact of earthquake forces on structures by increasing their natural vibration period and enhancing their damping capacity. While typical isolation systems are primarily designed for horizontal ground motions, the vertical component is often neglected unless specific regulations mandate its consideration. However, in near-fault zones, vertical ground motions can exceed horizontal ones, potentially affecting seismically isolated structures. This study examines the influence of vertical seismic forces on isolated buildings in near-fault zones, focusing on the reconstruction of Castelluccio di Norcia, a historic Italian village severely damaged during the 2016 Central Italy earthquake. The reconstruction involves an "Isolated Artificial Ground" system, a stepped reinforced concrete platform upon which buildings rest, separated from the ground by curved surface slider devices. To evaluate its dynamic response under various seismic events, a finite element model was developed and time-history analyses were conducted. Findings show that while vertical seismic component has minimal impact on horizontal displacements, it causes significant fluctuations in shear forces due to axial load variations and it influences also the frequency content of horizontal accelerations recorded on the platform. These results contribute to a better understanding of vertical seismic effects in near-fault scenarios and their implications for seismic isolation design.

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

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1. Introduction

Seismic isolation has become a mature and widely implemented strategy for both newly constructed buildings and the repair or reconstruction of structures damaged by earthquakes. These systems are designed to accommodate significant horizontal movements, effectively reducing the accelerations transmitted to the structure during seismic events. This is primarily achieved by increasing the natural vibration periods of the structure and enhancing the damping characteristics provided by the isolation devices. In contrast, in the vertical direction, traditional isolation devices behave much like simple support. As a result, the vertical response of an isolated structure generally mirrors that of a conventional fixed-base system. According to Italian building codes (“NTC18,” 2018), the vertical component of seismic motion must be taken into account only under certain conditions, specifically when the expected ground acceleration exceeds 0.15g and, for seismically isolated structures, when the ratio of vertical to equivalent horizontal stiffness is less than 800. In these cases, the vertical component should be considered if the vertical modes of vibration significantly engage the mass of the structure; otherwise, its influence can be considered negligible. However, the above prescriptions are not always cautious in near-fault regions, where the vertical seismic component can match or even exceed the horizontal one. In such locations, ground motion is strongly influenced by factors such as fault type and rupture dynamics conditions typically absent at greater distances from the fault.

Extensive research on these phenomena (Bozorgnia and Campbell, 2016; Gülerce et al., 2017; Petricca et al., 2021; Ramadan et al., 2021) has demonstrated that ground motions in near-fault regions are considerably more intense than those observed at greater distances from the fault. In some cases, the vertical component has been found to exceed twice the amplitude of the horizontal ones (Erdik et al., 2023; Tentella et al., 2024).

Despite this evidence, current building codes offer limited guidance for the definition of seismic actions for near-fault areas. In most seismic design standards, procedures for near-fault regions remain essentially identical to those used for medium- and far-fault sites, relying mainly on standard site response spectra prescribed by the codes.

This paper investigates the influence of the vertical component of the earthquake on the performance of seismically isolated structures located in near-fault regions. The reconstruction project of Castelluccio di Norcia is presented as a case study due to its proximity to an active fault responsible for the 2016 Central Italy’s earthquake with a magnitude of Mw = 6.5. The project aims to rebuild part of the historic center damaged by the earthquake using an "Artificial Ground Isolation" solution, where buildings are set on a stepped plate foundation isolated by Curved Surface Sliders (CSSs). A Finite Element Model (FEM) and nonlinear time-history analyses with NTC18-compliant seismic inputs were used to evaluate the seismic structural response.

2. Case study description

After the 2016 seismic events in Central Italy, especially the earthquake on October 30th, the village of Castelluccio di Norcia suffered extensive damage and numerous failures. As part of the ongoing reconstruction project, a reinforced concrete slab, supported by CSSs isolation devices, is planned to be installed in the historic centre, which is the most severely affected area. This plate will serve as a shared foundation, offering seismic isolation for all the reconstructed structures above it (Mezzi and Fulco, 2023). Given the iconic status of Castelluccio di Norcia and its significance as a tourist destination, maintaining the village's pre-earthquake layout is a primary objective of the reconstruction project. To support this goal, the isolated plate has been equipped with a sequence of stepped levels, ensuring that the original skyline of the village remains intact (Fig. 1).

The FEM model was developed in SAP2000 (“SAP2000,” 2025) using shell elements for the stepped plate and nonlinear links for the CSS devices. Isolators with a 3 m curvature radius and 3.5% friction coefficient were positioned in a 5 m × 5 m rough grid. Shells have an irregular mesh to matching the isolators layout, and the mesh refinement was defined based on preliminary analysis, balancing results reliability and computational efficiency. To accurately represent the dynamic interaction between the plate and the overlying aggregates, the latter were modelled in a simplified form by considering Multi-Degree-Of-Freedom (MDOF) oscillators consisting of frame elements. MDOF oscillators were carefully calibrated to effectively replicate the influence of actual buildings on the plate, specifically regarding base shear and overturning moment. Fig. 2 provides a schematic illustration of the developed numerical model.

3. Selection and scaling of the seismic input

Time history analyses, which account for the nonlinear dynamic responses of the system, involve integrating equations of motion and require the definition of acceleration time histories as input. Many seismic design standards internationally accept artificial, simulated, or natural time histories as inputs if these are consistent with the elastic spectrum relevant to the site. The Italian code requires the use of at least seven seismic events, requiring that their average Square Root of the Sum of Squares (SRSS) spectrum for the horizontal components matches the site spectrum amplified by a coefficient α, which is typically 1.3 and does not exceed $\sqrt{2}$. This spectrum must be within a specified range, that is +30% and -10% of the amplified code site spectrum. For the criterium matching, a linear scaling of the accelerograms is allowed. The adopted seismic events are selected using a software to match the Collapse Limit State (CLS) horizontal elastic spectrum specified by NTC18 for the site of Castelluccio di Norcia. The compatibility of the vertical components of the selected events was checked afterward, as the search tool cannot assess vertical spectrum compatibility. Table 1 reports data of the selected records and the scaling factors used for both seismic event components while Fig. 3 presents the scaled spectra.

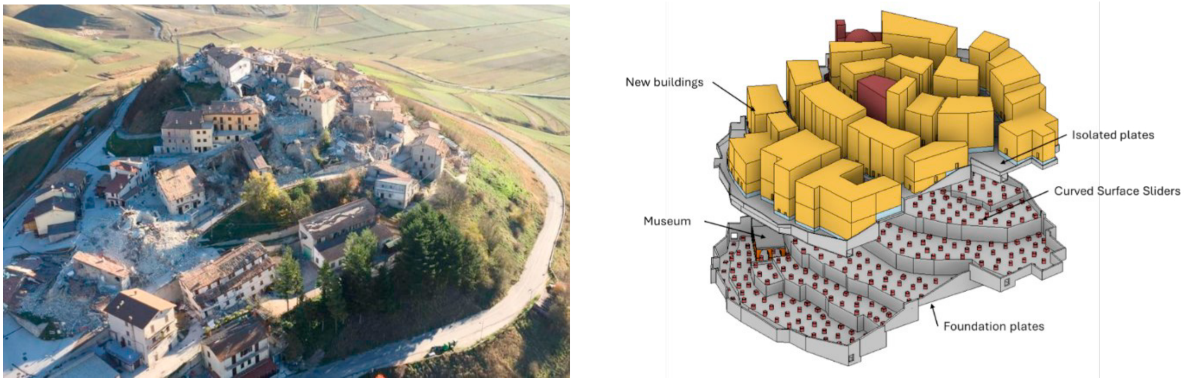


Fig. 1. Castelluccio di Norcia after the 30/10/2016 seismic event *(left)*; Reconstruction project of Castelluccio di Norcia *(right)*

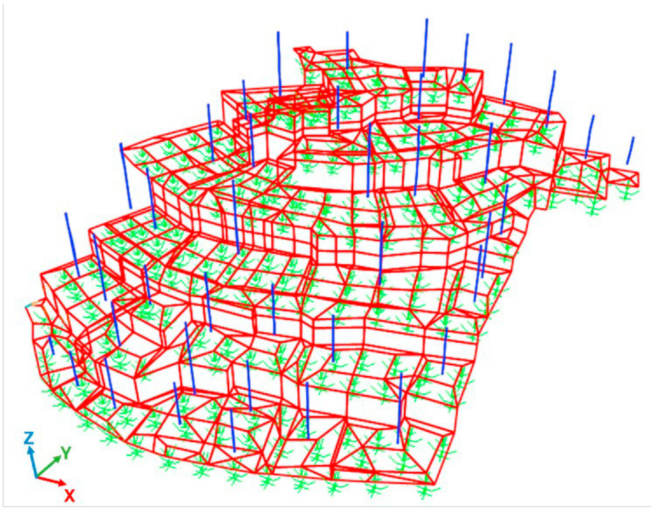


Fig. 2. FEM model of the reconstruction project of Castelluccio di Norcia

Table 1. Load cases used in direct integration analyses

Load Case	Network	Station Code	Date	Magnitude (Mw)	Scale Factor (Horizontal)	Scale Factor (Vertical)
TH1	3A	MZ24	30/10/2016	6.6	1.4	2.31
TH2	IT	CLO	30/10/2016	6.6	1.1	0.77
TH3	TK	2708	6/2/2023	7.7	0.7	0.93
TH4	TK	2718	6/2/2023	7.7	0.8	1.01
TH5	TK	3137	6/2/2023	7.7	1.3	1.3
TH6	TK	3142	6/2/2023	7.7	0.7	1.3
TH7	TK	4616	6/2/2023	7.7	1.3	1.57

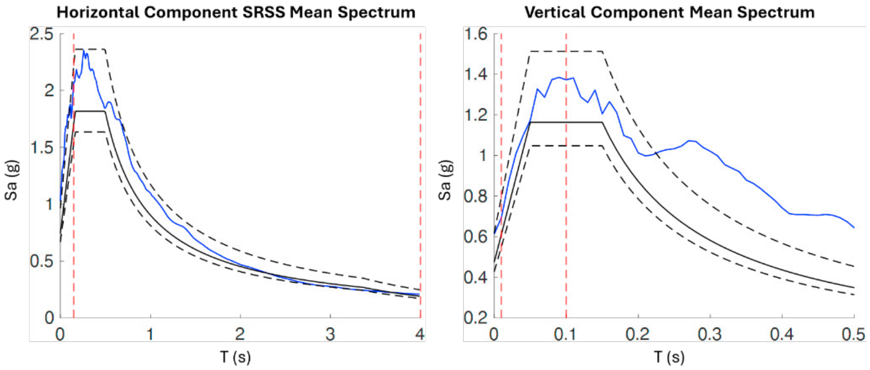


Fig. 3. Scaled average spectra of horizontal (SRSS) and vertical component

As illustrated in Fig. 3, the selected scaling factors guarantee that the average spectrum is compatible with the site one within the full range of periods of interest (red dashed lines in Fig. 3); for the horizontal component, the period range 0.15 s - 1.2 T_{iso} (equal to 3.31 s) is considered, consistently with code requirements. Regarding the vertical component, the standards do not explicitly specify a mandatory period range for the compatibility check; consequently, the selected period range (0.01 s to 0.1 s) is obtained from the vertical vibration periods of both isolation systems and buildings.

4. Results of Fast Nonlinear Analyses (FNA)

This section presents results obtained from Fast Nonlinear Analyses performed in SAP2000 (“SAP2000,” 2025). In order to study the effect of the vertical component of seismic action on the structural response, analyses are performed by including and disregarding in turn the vertical actions. Table 2 presents, for four selected devices (Fig. 4), the mean values of displacement derived from both analyses, calculated by averaging the maximum displacements recorded for each event.

Table 2. Resultant displacements obtained with vertical component for the selected devices

N° of isolator	Mean displacements with vertical component (m)	Mean displacements without vertical component (m)
ISO1	0.442	0.440
ISO2	0.440	0.438
ISO3	0.440	0.438
ISO4	0.442	0.440

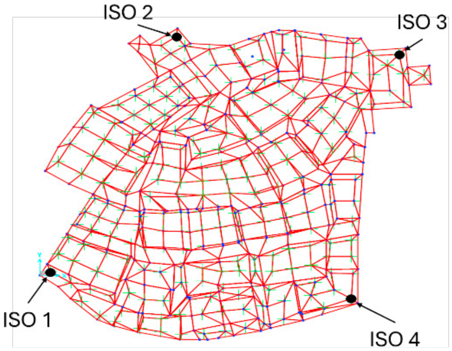


Fig. 4 Selected devices on the isolated slab

Displacements are nearly the same for all the isolators, indicating that the plate acts as a horizontally rigid element with negligible torsional effects and no relative movement between supports. More importantly, the mean horizontal displacement remains essentially unchanged regardless of whether the vertical component is considered.

Fig. 5 presents the force-displacement cycles in X and Y directions of an isolator subjected to TH2 and TH3, obtained by including and disregarding the vertical component of seismic action. The hysteretic cycles show that displacements remain mostly unaffected by the vertical component, but shear forces change significantly. The earthquake vertical component causes sudden fluctuations in device shear forces due to variations in axial loads, leading to corresponding changes in friction during horizontal motion. Fig. 6 presents two histograms comparing axial load ratios on the devices: mean axial loads from THs versus Vertical loads at Seismic Condition (VSC) are presented in the first histogram and axial loads from the static Ultimate Limit State (ULS) combination versus VSC are showed in the second one. On average, TH/VSC ratios are higher and exhibit greater dispersion compared to ULS/VSC ratios. Earthquake vertical components can double vertical loads, meaning vertical earthquakes play a significant role in the individual design of the isolation devices. However, from an average point of view, the effects of the vertical actions on the overall design of the isolation system is less evident; Table 3 reports the average and maximum values of the axial forces on the isolators, obtained from the seismic combinations THs and ULS, which must be always taken in to account in the isolators design. It can be observed that, although there is a significant discrepancy between the maximum vertical forces resulting from the two combinations, the difference in average values is less pronounced. Consequently, it can be concluded that, form an overall point of view, the inclusion of the vertical component does not lead to a more demanding selection of devices and, consequently, to increased costs. On the contrary, it is fundamental for the individual sizing of the devices.

Another interesting issue concerns the comparison of results of the two analyses is in terms of frequency content of acceleration time histories registered on the plate. In order to also provide some indications concerning the seismic action experienced by building lying on the plate, the above comparison is shown in terms of pseudo-acceleration response spectra. Fig. 7 compares the response spectra of the acceleration time histories for TH3 obtained on one step of the isolated slab for each direction with the relevant spectra of accelerations applied at the base. In order to average motions at different locations, the response spectra are obtained by averaging time histories of accelerations registered in different position on the same step. Plots on the left column refer to the model including the vertical excitation while plots on the right column refer to the model in which the vertical component is neglected. In the horizontal response spectra obtained from the analysis including the vertical actions, it is possible to observe the presence of acceleration peaks at short periods. These effects are induced by low-period horizontal-vertical coupled modes, which are activated by the introduction of a vertical input, characterised by high spectral ordinated at those periods. Furthermore, at high periods, the increase of the spectral ordinates due to the isolation system is also evident, as expected.

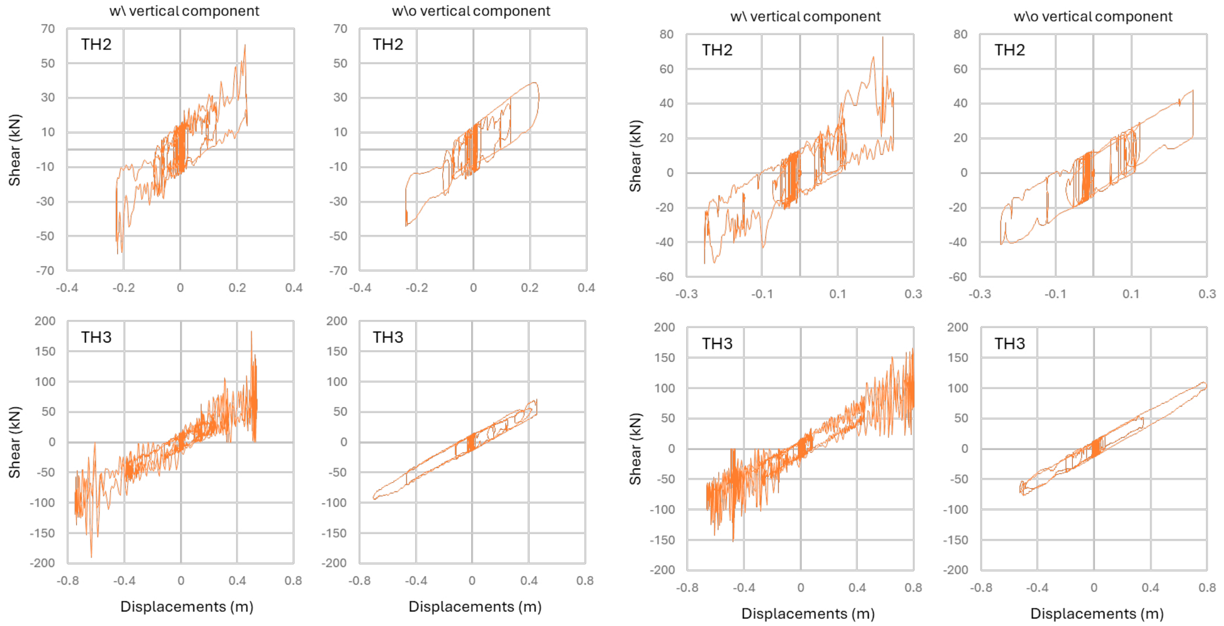


Fig. 5. Force-Displacement cycles obtained with and without the vertical component in X (left) and Y (right) direction.

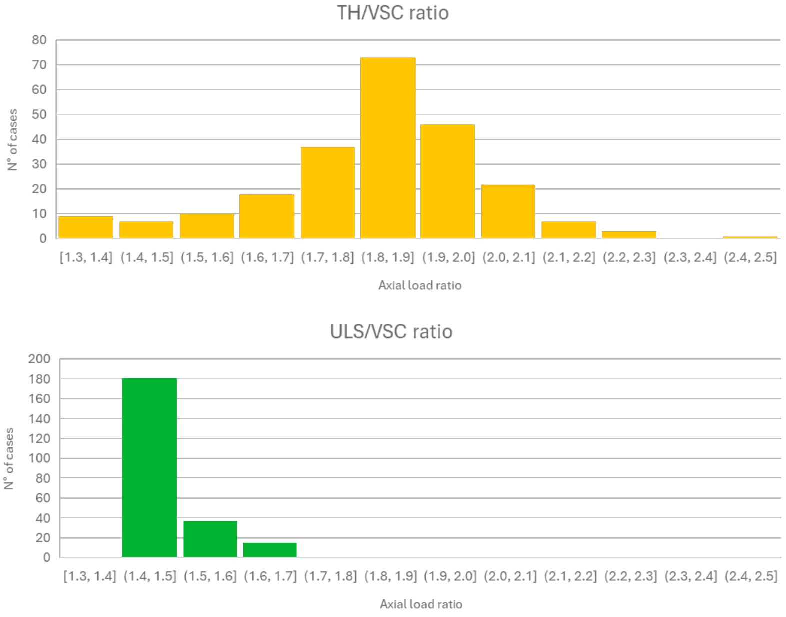
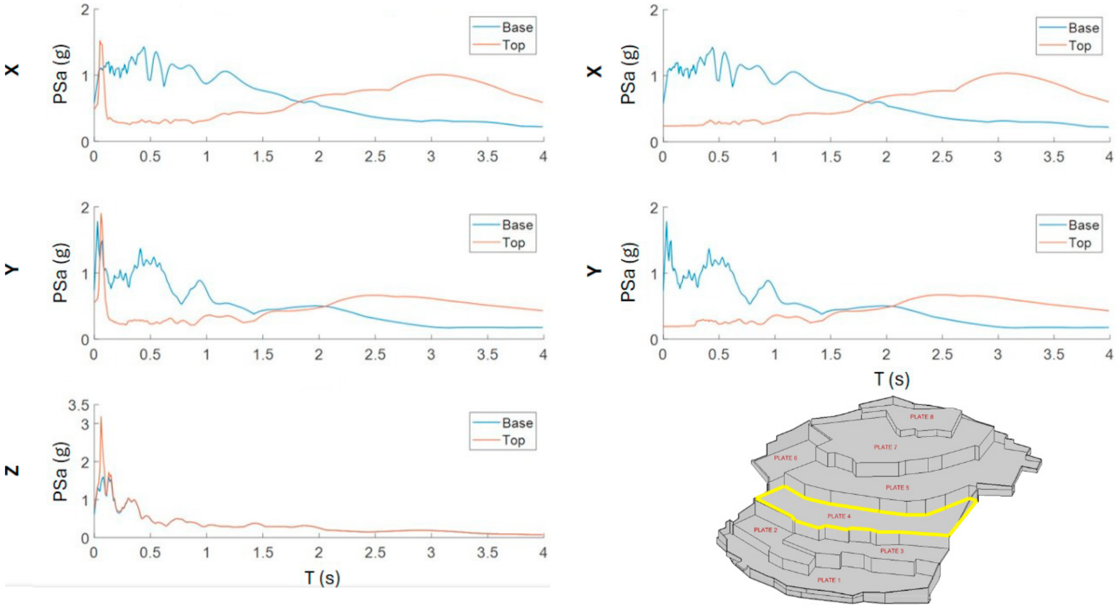


Fig. 6. Comparison of TH/VSC and ULS/VSC ratios

Table 3. Comparison of THs and ULS mean and maximum axial loads

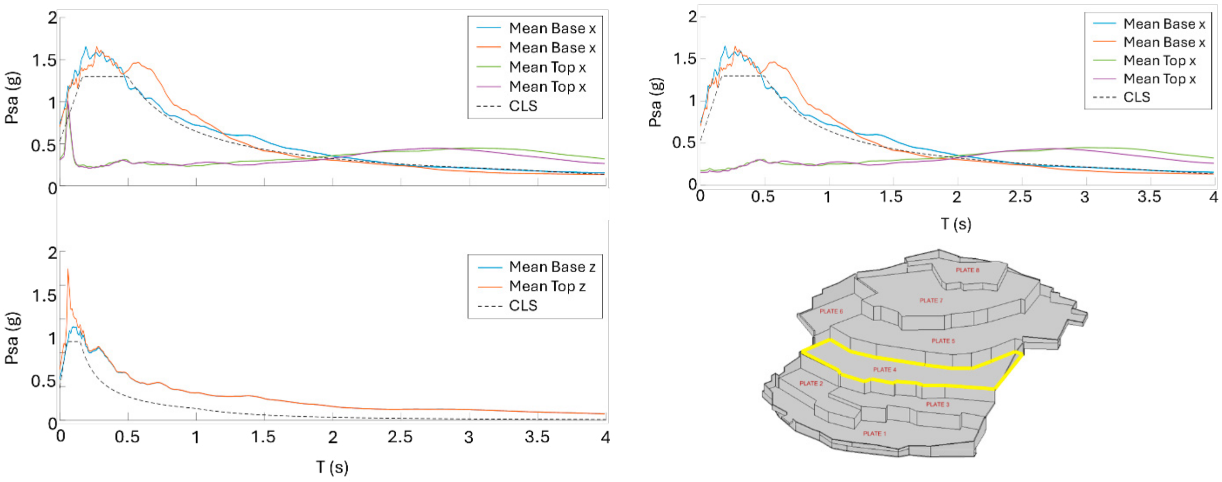
Case	Mean axial load (kN)	Max axial load (kN)
THs	3777.4	6600.2
ULS	3096.9	5412.3



(a) (b)

Fig. 7. Pseudo acceleration spectra of the signals at the base and on the top of the slab in the three directions resulting from analyses with vertical component (a) and without vertical component (b)

The interaction between the vertical and the horizontal dynamics of the slab is also evident from the mean pseudo acceleration response spectra obtained by averaging results from all the seven selected earthquakes (Fig. 8). From an overall point of view, the two analyses, with and without the vertical component of the actions, lead to the same results at mid to long periods. On the contrary, at short periods, amplifications of horizontal spectral ordinated are evident as a consequence of the vertical-horizontal coupling of the system. Notably, the acceleration peaks reach values that closely match those predicted by the site spectrum at the SLC.



(a) (b)

Fig. 8. Average over THs of pseudo acceleration spectra of the signals at the base and on the top of the slab in the horizontal (up) and vertical (down) directions resulting from analyses with vertical component (a) and without vertical component (b)

5. Conclusions

This research investigates the influence of the vertical component of seismic events on the performance of a seismically isolated structure located in a near-fault zone, with particular reference to the Castelluccio di Norcia reconstruction project. The analysis of structural response was carried out using Finite Element model and time-history simulations, integrating site-specific seismic inputs selected in accordance with NTC18 code.

The main findings of the study are as follows:

- including the vertical earthquake component made little difference in the horizontal displacements of the isolators.
- Although displacements were largely unchanged, the vertical component caused fluctuations in shear forces as a result of changes in axial loads on the isolators. These fluctuations, resulting from variations in vertical loads, producing instantaneous changes in the friction force within the isolation devices.
- Earthquake-induced vertical motions altered the load distribution on the isolators, increasing axial loads by up to approximately 30% compared to those considered in the ULS. However, since average axial loads remain close to those obtained from ULS combinations, the inclusion of vertical components, for this case, does not appear to significantly affect device selection in terms of overall cost.
- The vertical component of the earthquake interacts with the horizontal dynamics of the slab, causing amplifications of the horizontal accelerations at short periods.

Although the vertical component of seismic action does not significantly affect horizontal displacements in seismically isolated structures, this study shows that it influences the distribution of forces within the isolators and can alter the horizontal dynamic response by amplifying accelerations, depending on the system dynamics. Therefore, it should be considered during the design phase. The results highlight the need for further investigation and potential updates of seismic design codes, especially in near-fault areas where vertical accelerations may be particularly high.

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