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THREE-DIMENSIONAL SEISMIC INPUT FOR NEAR FAULT SCENARIOS AND EFFECTS ON STRUCTURES

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Abstract

Recent studies have enhanced the understanding of near-fault seismic effects on both horizontal and vertical components. The most common horizontal effect is fault-normal forward directivity, generating a strong, long-period pulse. Another effect is the fault-parallel fling, which appears as a displacement step with permanent ground deformation. In dip-slip faults, vertical slip also induces intense vertical velocity components. Eurocode 8 mandates considering near-source effects for strategic structures and bridges within 10 km of an active fault capable of producing earthquakes with Mw > 6.5. However, it lacks specific guidelines on deriving site-specific spectra. This study focuses on central Italy, a highly seismic area, analysing the October 30, 2016 (Mw 6.5). A three-dimensional Ground Motion Model (GMM), based on an extensive database, is used to define near-fault response spectra for distances up to 30 km. The study also evaluates the impact on structures, particularly vertical-sensitive ones, such as masonry, precast, and base-isolated buildings, which are highly affected by horizontal and vertical components.

Keywords: Instructions, ECCOMAS Thematic Conference, Structural Dynamics, Earthquake Engineering, Proceedings.

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1 INTRODUCTION

The vast amount of data collected in recent decades has significantly improved our understanding of the main effects of near-fault records, which affect both the horizontal and vertical components [1-2]. Regarding the horizontal components, the most common near-fault effect is fault-normal forward directivity. This occurs when the fault rupture propagates toward a site at a velocity approximately equal to the shear wave velocity. In this case, most of the energy arrives in a single, intense, relatively long-period pulse (bilateral velocity pulse). A second effect is the fault-parallel fling, which manifests as a unilateral velocity pulse with permanent final displacements. In dip-slip faults (reverse and oblique faults), slip also occurs along the vertical direction, generating an intense vertical velocity component.

In the European context, Eurocode 8 requires that near-source effects be considered for strategic structures [3] and bridges [4] when the site is located within 10 km horizontally of a known active seismotectonic fault capable of producing an earthquake with a Moment Magnitude (M_w) greater than 6.5. In such cases, site-specific spectra that account for near-source effects must be used, as standard design spectra do not typically consider the increased seismic demand in near-field sites. However, no specific guidance is provided on how to derive these spectra.

This study focuses on the central Italian region, one of the most seismically active areas in Italy. Specifically, earthquake records from the 2016 seismic sequence are first analysed, with particular attention given to the October 30th event (M_w = 6.5) with an epicentre near Norcia, to observe near-source effects. Then, to address the limitations of current seismic codes, which lack specific guidelines, an appropriate seismic input for near-fault sites has been defined. For this purpose, a recently developed three-dimensional Ground Motion Model (GMM), based on an extensive near-fault ground motion database [5-7], has been employed. Using this approach, specific near-fault response spectra have been developed for varying distances from the fault (ranging from 0 km to 30 km) to provide a preliminary estimate of their impact on structures. Different types of vertical-sensitive structures, such as masonry and precast structures, have been considered. Additionally, base-isolated structures have been analysed, as their failure is particularly sensitive to the combined effects of horizontal and vertical components [8-10].

2 2016 CENTRAL ITALY EARTHQUAKE

In 2016, central Italy was struck by a seismic sequence consisting of two mainshocks: Mw 6.0 on August 24 and Mw 6.5 on October 30. The latter event matches the Eurocode threshold for considering near-fault effects within a 10 km radius. For this reason, records from stations closest to the epicentre have been analysed to identify potential near-source effects. Specifically, three stations were considered: Castelluccio di Norcia (CLO), Forche Canapine (FCC), and Norcia (NRC), located 6.9 km, 10.9 km, and 5 km from the epicentre, respectively (Figure 1). Both horizontal and vertical components were analysed using pseudo-acceleration response spectra (Figure 2a). Additionally, displacement spectra were computed for the horizontal components (Figure 2b). The results show that the vertical response spectra (U-D) reach very high values in the short-period range, exceeding 1g at CLO and FCC stations. Despite being closer to the epicentre, NRC exhibits a lower vertical component due to its position relative to the fault plane projection, as discussed in [8]. Regarding horizontal components, the FCC station recorded the highest pseudo-acceleration demand, while the largest displacement was observed in the E-W component recorded by the CLO station. However, displacements were not excessive, as they do not significantly increase for periods longer than 2s, according to the moderate fault plane dimension [11].

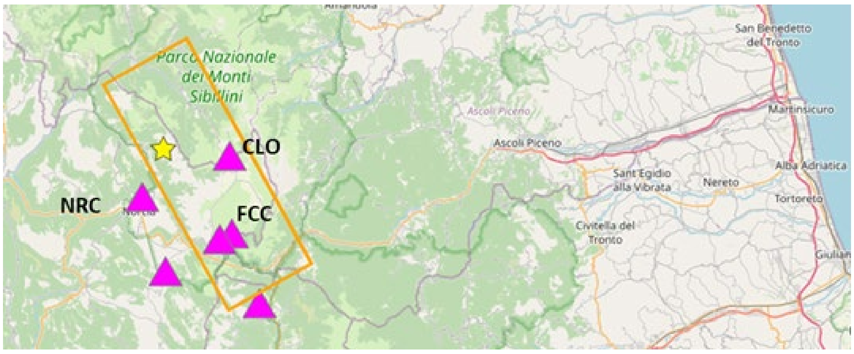
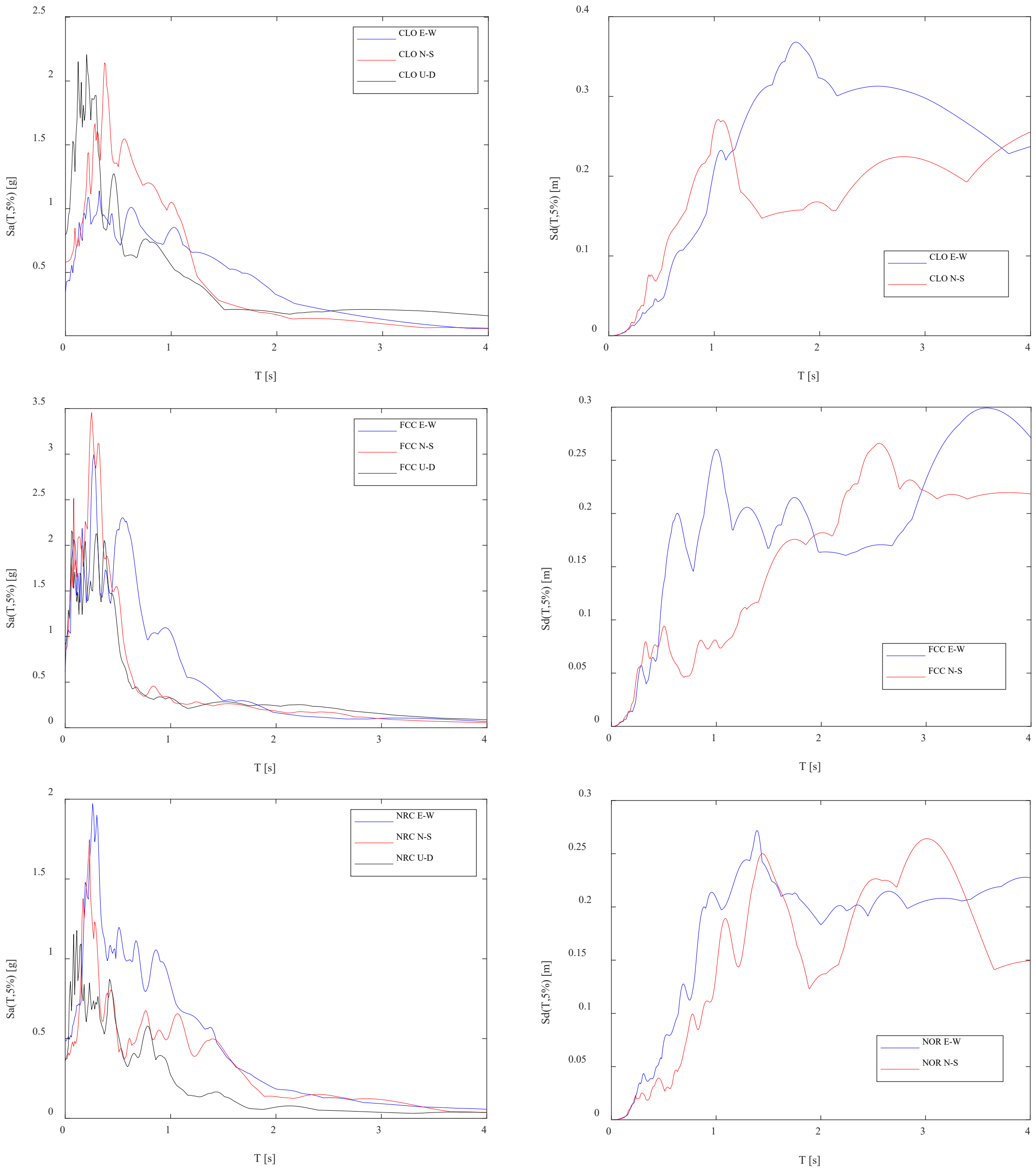


Figure 1. Seismic station code and location



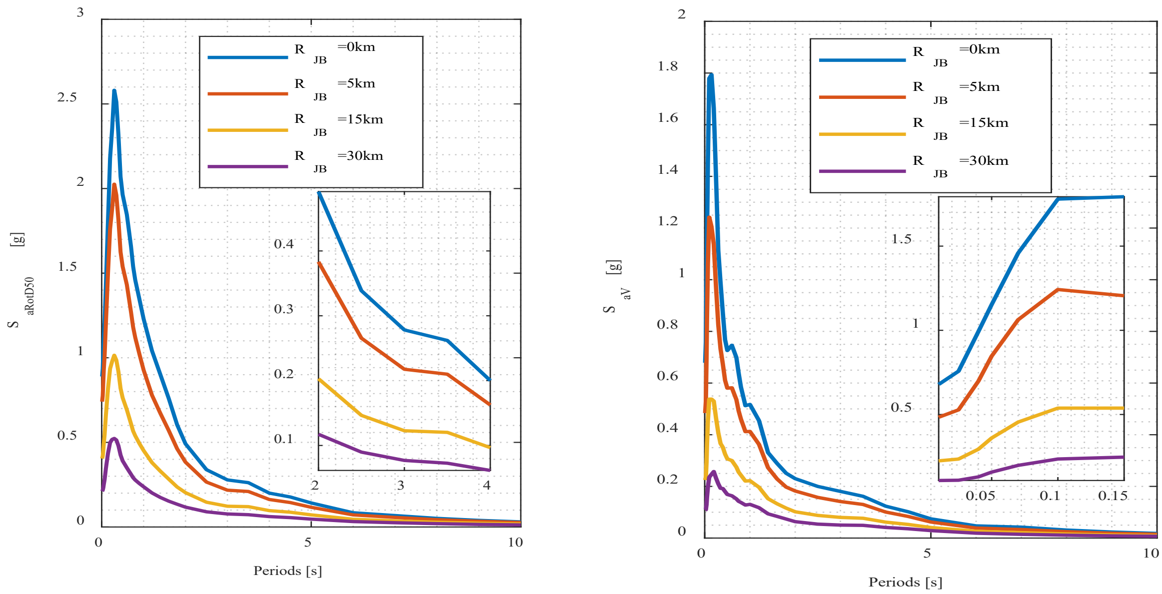
(a) (b)

Figure **2**. Response spectra in terms of pseudo-acceleration a) and horizontal displacement b)

These findings suggest that even if the horizontal displacement demand is modest compared to other near-fault events with higher magnitudes (such as the 6th February 2023 earthquake in Turkey), the vertical component is significant and could play a crucial role in structural response. Finally, it is worth noting that similar conclusions can be drawn from other Italian seismic events, such as L'Aquila 2009 [13] and Emilia 2012 [14], while in the Turkish event horizontal effects (pulse-like records) are prevalent and only in few stations a large vertical component has been registered [15].

3 NEAR-SOURCE INPUT AND EFFECT ON STRUCTURES

The approach adopted in this study to derive horizontal and vertical response spectra for near-fault sites involves selecting an appropriate seismic scenario (consistent with the site) and suitable ground motion models (GMMs) that account for near-fault effects. For the horizontal component, this study utilizes the ITA18 model [5], a regional ground motion model for Italy, empirically adjusted for near-field effects by [6] using the global NESS2.0 database. For the vertical component, the V/H ratio defined by [7] has been applied, incorporating an adjustment term to enhance predictions in near-source scenarios. This modified model, referred to as ITA18-V(VH)-NESS, is used alongside ITA18 to generate vertical response spectra consistent with the horizontal ones. The analysis focuses on the CLO site, representative of a high-seismicity area in the Apennine chain of central Italy, associated with a maximum earthquake magnitude of Mw 7.4. Other parameters include a shear wave velocity (VS,30) of 300 m/s in the upper 30 meters of subsoil and four Joyner-Boore distances (0, 5, 15, and 30 km). The intensity measure (IM) used for defining horizontal spectra is spectral acceleration in terms of RotD50, which represents the median spectral acceleration across all orientations, providing a robust measure of bidirectional horizontal ground motion [16]. The resulting response spectra for Mw 7.4 are shown in Figure 3 for both horizontal and vertical components in terms of pseudo-acceleration. It is worth noting that, unlike other less recent models, these GMMs are defined for periods up to 10 seconds. The figures include zoomed-in views of the 2s-3s and 0s-0.15s period ranges for the horizontal and vertical spectra, respectively, that will be useful later for commenting the effects on base-isolated structures.

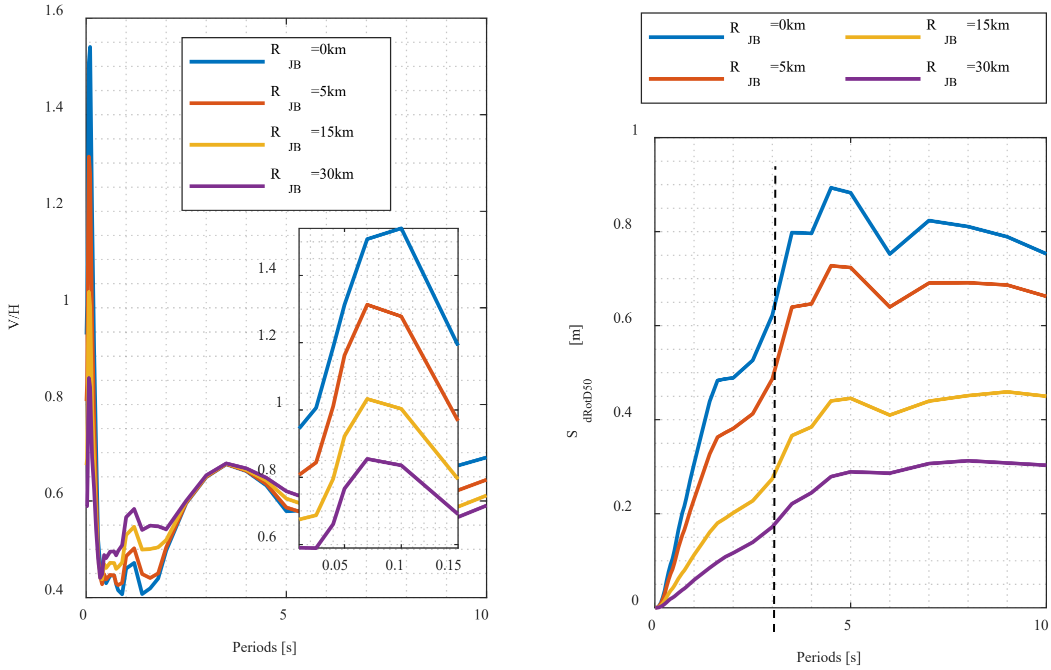


a) b)

Figure **3**. Horizontal a) and vertical b) response spectra in terms of pseudo-acceleration

Regarding the vertical component, it is important to highlight that for distances of 0 km and 5 km, both within the 10 km threshold set by Eurocode 8 [3-4] for near-source effects, the maximum pseudo-acceleration in the critical range significantly exceeds 1g and that for very short periods, it surpasses the pseudo-acceleration of the horizontal component as shown in Figure 4a, where the V/H ratio (the ratio between vertical and horizontal spectral accelerations) exceeds 1. This implies that, for structures showing vertical periods within this range, vertical action dominates, potentially causing gravity loads to vanish. Since the axial stiffness of masonry walls or reinforced concrete (RC) columns are usually very high vibration, periods of both masonry and RC buildings in the vertical direction are typically very short, thus, if subjected to near-fault earthquakes they may experience complete unloading. For structures unable to resist tensile forces, such as masonry or precast RC buildings (without mechanical connections between beams and columns), this means that at certain moments, horizontal resistance is lost due to the absence of friction forces. As a result, the structure may experience local or global collapse, as documented by [13] for masonry structures subjected to 2016 Central Italy seismic sequence and [14] for precast industrial buildings subjected to 2012 Emilia seismic sequence. RC structures behave differently since columns can resist tensile forces, however, even in this case large vertical actions can cause severe damage to these buildings (ref di Sarno), due to excessive tensile or compressive forces of RC columns.

Additionally, it is even more noteworthy that similar damage or collapse mechanisms may occur in base-isolated buildings near active faults, if near-source effects are not properly considered in the design, as recently highlighted by several authors [17]. This is a potential vulnerability of base-isolated buildings, which are more and more built in high-seismicity zones (thus near potential faults) due to the high level of protection they offer. The issue arises because isolation bearings have low lateral stiffness (to ensure a long isolation period) but very high vertical stiffness. As a result, their vertical periods are similar to those of fixed-base structures, placing them within the critical range of the vertical pseudo-acceleration spectrum. More specifically, in buildings with concave curved surface bearings (CCSBs), the main concern is bearing uplift, which is not allowed by the codes since it can increase significantly axial compression forces due to dynamic amplification effects and reduce the global friction force, leading to greater horizontal displacements. For high-damping rubber bearings (HDRBs), which can withstand moderate tensile forces, the main risks include excessive tension (larger than limit imposed by codes) and significant axial compression forces, which in combination to large horizontal displacement demands may lead to bearing buckling. To better illustrate this later issue, Figure 2b presents response spectra in terms of displacement, referring to an equivalent damping ratio of 5%. For an isolation period of 3s (T_{is}=3s) the displacement of the isolation system is 0.5m at 0 km and 0.65m at 5 km. According to national code and Eurocode (ref), applying a reduction coefficient of 0.7 for an equivalent damping ratio of 15% (typical for HDRBs) results in displacements of 0.35m and 0.45m, that are still significantly large values. Therefore, large-diameter isolators must be used to prevent bearing buckling, which in turn requires a greater number of low-friction flat sliders to maintain a sufficiently long isolation period for horizontal seismic action. The problem becomes even more critical in multi-story buildings, where horizontal seismic action can also induce significant variations in axial forces on the isolators due to the rocking phenomenon. Finally, is should be noted that for that distances (less than 5 km) horizontal pseudo-accelerations corresponding to (T_{is}=3s) are 0.225g and 0.375g (Figure 2). Values reduced by 0.7 are 0.16g and 0.26g, that are not negligible for the design of the superstructure.



a) b)

Figure **4**. Response spectra in terms of V/H ratio a) and Horizontal displacement b)

4 CONCLUSIONS

- The analysis carried out in this paper confirms that near-fault effects significantly influence both horizontal and vertical seismic demand, however the Italian event (Mw 6.5) showed a moderate horizontal displacement demand while the vertical pseudo-acceleration proved to be particularly intense, exceeding 1g in some cases.
- Most of structures (both masonry and r.c.) have a low vertical vibration period thus they are particularly vulnerable to near-fault vertical accelerations; moreover they are especially at risk if they do not resist to tension force (such as masonry buildings, precast structures without mechanical connections between beams and columns) due to the loss of frictional resistance under vertical seismic action.
- Base-isolated buildings, typically designed for horizontal seismic protection, may suffer from significant vertical accelerations in near-fault conditions: CCSBs (Concave Curved Surface Bearings) are prone to uplift, increasing axial compression and horizontal displacements, while HDRBs (High-Damping Rubber Bearings) face risks of excessive tensile forces and potential buckling under combined vertical and horizontal demands.
- Current seismic codes, including Eurocode 8, acknowledge near-source effects but lack clear guidelines for defining near-fault response spectra; they should incorporate advanced ground motion models (GMMs) that account for near-fault effects on both horizontal and vertical components as well as an appropriate procedure for selecting a set of accelerograms simultaneously matching the horizontal and vertical target spectra.
- Special indication should be also given for base-isolated structures built in near-fault regions, thus further studies are needed to refine and improve code provisions for base-isolated structures exposed to near-fault ground motions.

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