9th FTSES 2024 Penghu, Taiwan

9th France-Taiwan Symposium in Earth Sciences
Session: Earthquake and Seismotectonics

Insights into Nonlinear Site Behavior: A Comprehensive Analysis Using Response Curves and 3D Nonlinear Numerical Modelling

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The understanding of earthquake ground motion amplification in soft sediments, influenced by the contrasting physical properties of rock and soil, faces challenges posed by nonlinear site responses. Nonlinear effects, driven by stress-strain behavior in soils under substantial loads, lead to altered propagation velocity, shifts in predominant frequency, increased damping, and reduced amplification. Identifying and modeling the nonlinearity in earthquake ground motion, however, poses significant challenges. Consequently, many studies on ground motion prediction commonly resort to using empirical equations, which simplify the incorporation of nonlinearity by relying on proxies such as the time-averaged shear-wave velocity to a depth of 30 meters (Vs30) , peak ground acceleration (PGA) and others. In this study, we introduce a novel approach to unveil nonlinear site responses by analyzing resonance curves extracted from waveforms recorded during weak to strong ground motions at surface stations. This method reveals spatial patterns of nonlinearity and highlights susceptible regions within the shallow subsurface. Validation through KiK-net borehole responses demonstrates the robustness of our methodology in extracting site characteristics from the shallow subsurface. Additionally, introducing 3D numerical simulations with spectral element code SPEED provides insights into the principal causes of nonlinear behavior. These simulations emphasize the impact of local site properties and elucidate frequency shifts caused by nonlinear effects across low to high frequencies. By combining findings from nonlinear numerical modeling with response curve analysis using real data, we establish and refine the relationship of proxies. This contribution aims to advance seismic engineering and ground motion prediction studies, facilitating precise seismic hazard assessments.

Keywords: seismic site effects; 3D numerical modelling on wave propagation; nonlinear site response; predominant frequency