ARTIFICIAL INTELLIGENCE

Deep learning generative strategies to enhance 3D physics-based seismic wave propagation: from diffusive super-resolution to 3D Fourier Neural Operators.

Publié le 14 avril 2024 - European Geophysical Union General Assembly 2024

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Estimating the seismic hazard in earthquake-prone regions, in order to assess the risk associated to nuclear facilities, must take into account a large number of uncertainties, and in particular our limited knowledge of the geology. And yet, we know that certain geological features can create site effects that considerably amplify earthquake ground motion. In this work, we provide a quantitative assessment of how largely can earthquake ground motion simulation benefit from deep learning approaches, quantifying the influence of geological heterogeneities on the spatio-temporal nature of the earthquake-induced site response. Two main frameworks are addressed: conditional generative approaches with diffusion models and neural operators. On one hand, generative adversarial learning and diffusions models are compared in a time-series super-resolution context [1]. The main task is to improve the outcome of 3D fault-to-site earthquake numerical simulations (accurate up to 5 Hz [2, 3]) at higher frequencies (5-30 Hz), by learning the low-to-high frequency mapping from seismograms recorded worldwide [1]. The generation is conditioned by the numerical simulation synthetic time-histories, in a one-to-many setup that enables site-specific probabilistic hazard assessment. On the other hand, the successful use of Factorized Fourier Neural Operator (F-FNO) to entirely replace cumbersome 3D elastodynamic numerical simulations is described [4], showing how this approach can pave the way to real-time large-scale digital twins of earthquake prone regions. The trained neural operator learns the relationship between 3D heterogeneous geologies and surface ground motions generated by the propagation of seismic wave through these geologies. The F-FNO is trained on the HEMEW-3D (https://github.com/lehmannfa/HEMEW3D/releases) database, comprising 30000 high-fidelity numerical simulations of earthquake ground motion through generic geologies, performed by employing the high-performance code SEM3D [4]. Next, a smaller database was built specifically for the Teil region (Ardèche, France), where a MW 4.9 moderate shallow earthquake occurred in November 2019 [4]. The F-FNO is then specialized on this database database with just 250 examples. Transfer learning improved the prediction error by 22 %. According to seismological Goodness-of-Fit (GoF) metrics, 91% of predictions have an excellent GoF for the phase (and 62% for the envelope). Ground motion intensity measurements are, on average, slightly underestimated. [1] Gatti, F.; Clouteau, D. Towards Blending Physics-Based Numerical Simulations and Seismic Databases Using Generative Adversarial Network. Computer Methods in Applied Mechanics and Engineering 2020, 372, 113421.https://doi.org/10.1016/j.cma.2020.113421. [2] Touhami, S.; Gatti, F.; Lopez-Caballero, F.; Cottereau, R.; de Abreu Corrêa, L.;Aubry, L.; Clouteau, D. SEM3D: A 3D High-Fidelity Numerical Earthquake Sim-ulator for Broadband (0–10 Hz) Seismic Response Prediction at a Regional Scale.Geosciences 2022, 12 (3), 112. https://doi.org/10.3390/geosciences12030112. https://github.com/sem3d/SEM [3] Gatti, F.; Carvalho Paludo, L. D.; Svay, A.; Lopez-Caballero, F.-; Cottereau, R.;Clouteau, D. Investigation of the Earthquake Ground Motion Coherence in Het-erogeneous Non-Linear Soil Deposits. Procedia Engineering 2017, 199, 2354–2359.https://doi.org/10.1016/j.proeng.2017.09.232.[4] Lehmann, F.; Gatti, F.; Bertin, M.; Clouteau, D. Machine Learning Opportunities to Conduct High-Fidelity Earthquake Simulations in Multi-Scale Heterogeneous Geology.Front. Earth Sci. 2022, 10, 1029160. https://doi.org/10.3389/feart.2022.1029160. [4] Lehmann, F.; Gatti, F.; Bertin, M.; Clouteau, D. Fourier Neural Operator Sur-rogate Model to Predict 3D Seismic Waves Propagation. arXiv April 20, 2023.http://arxiv.org/abs/2304.10242 (accessed 2023-04-21).