An Elaborate Seismic Study of Beirut: Integrating 3D Multidisciplinary Geotechnical Model Definition, Machine Learning Enhancements, and Numerical Simulations

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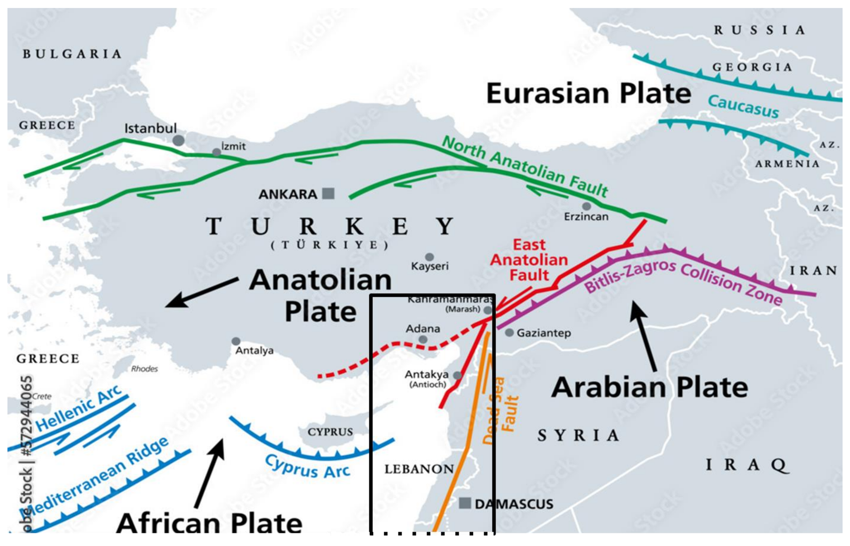
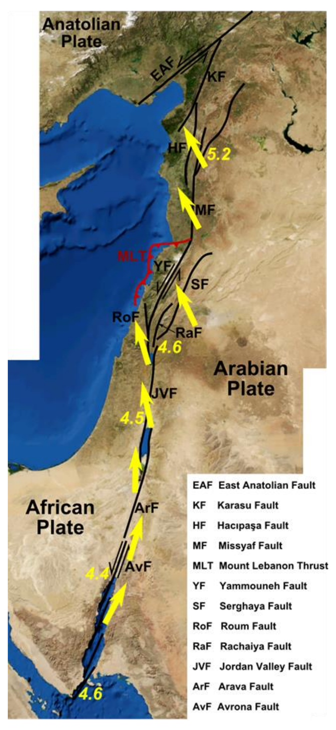
Introduction

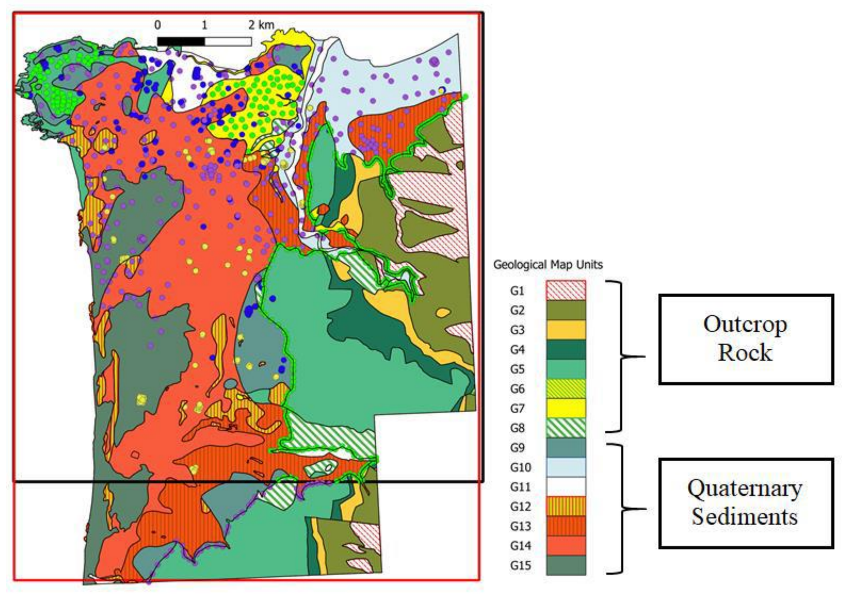
Beirut's history of earthquakes, coupled with its varied soil compositions, underscores the need for advanced seismic hazard models. Traditional assessment methods (Vs30 proxies) often underestimate the risks due to the city's geological complexities. Recognizing these challenges, our research integrates comprehensive geotechnical data, innovative machine learning techniques, and detailed numerical simulations to develop an elaborate 3D geotechnical model of Beirut. This model aims to provide a more accurate representation of seismic risks, facilitating improved urban planning and risk mitigation efforts.



Tectonic Setting in the Middle East highlighting the major fault lines – the North Anatolian Fault, East Anatolian Fault, and the Dead Sea Fault. The intersection of the Eurasian, Arabian, and African plates creates a complex seismic landscape impacting the region, including Lebanon."



Gomez F. et al 2007



Geological Map of Greater Beirut with Data Points. This map delineates various geological units within the region, each color-coded to represent distinct types. Data points on the map indicate borehole locations, differentiating between those that have reached bedrock (blue dots), those that have not (yellow dots), virtual boreholes (green dots), and sites of H/V geophysical measurements (purple dots).

3D Velocity Model Construction: Approach and Outcomes

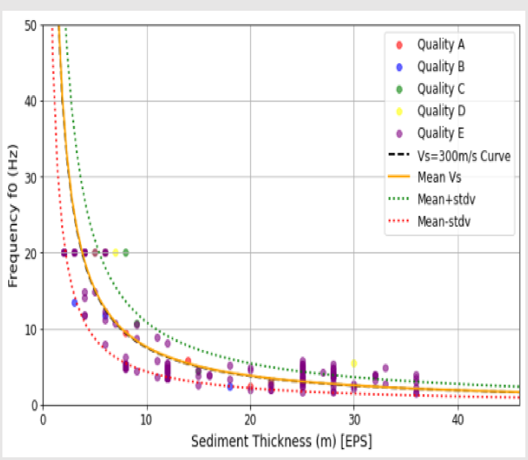
3D Geotechnical Model Development:

Data from **500+ boreholes** and **700+ geophysical measurements** were used alongside **refined Digital Elevation Models (DEM)** and **geological data** to build an extensive 3D model of Beirut's subsurface.

Mean Shear wave velocity Estimation

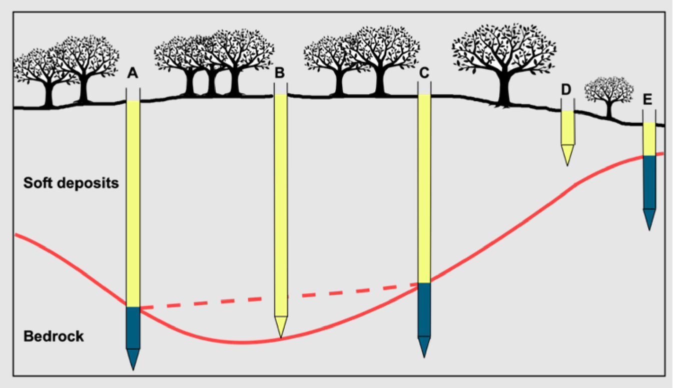
Vs_mean was derived from sediment thickness and fundamental frequency data (EPS and f0). Utilizing Nakamura's approach, a standard Vs_mean of 300 m/s was established, with a Quality Factor (QF) ensuring data reliability across Beirut's varied geological structure.

$$f_0 = \frac{V_S}{4.EPS}$$



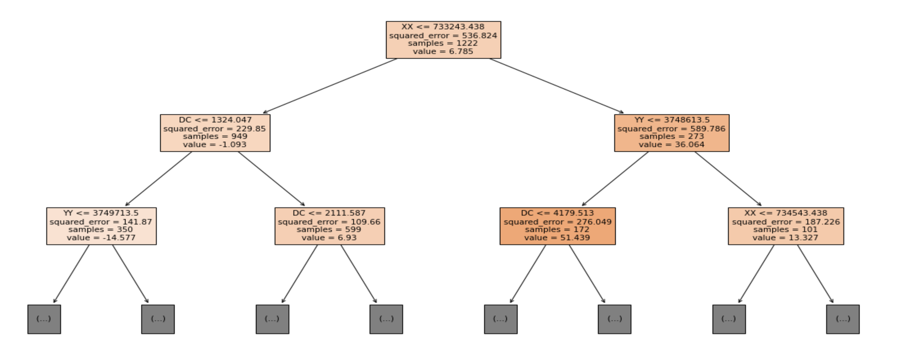
Iterative Approach for Bedrock Modeling

Initial bedrock surfaces are interpolated from borehole and H/V data. These surfaces are cross-checked against sediment depths from incomplete boreholes to prevent underestimation of bedrock depths. Should the interpolation exceed known bedrock highs, the model is adjusted and re-interpolated. Convergence is indicated when the model no longer surpasses these known elevations. This cyclic refinement continues until the model aligns with all established bedrock data, enhancing accuracy and reducing uncertainty.

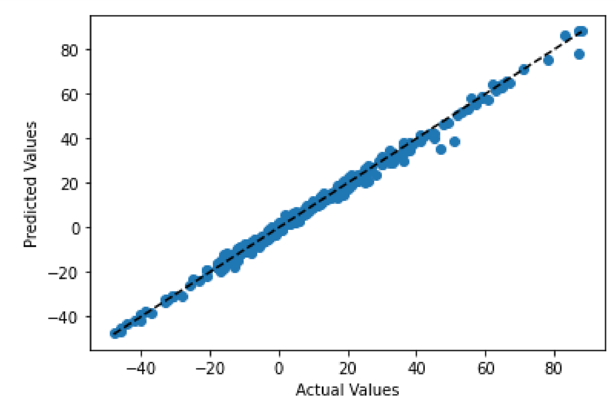


Machine Learning Enhancements:

A Random Forest algorithm was employed to represent sedimentary units continuously, significantly benefiting regions with sparse data coverage.

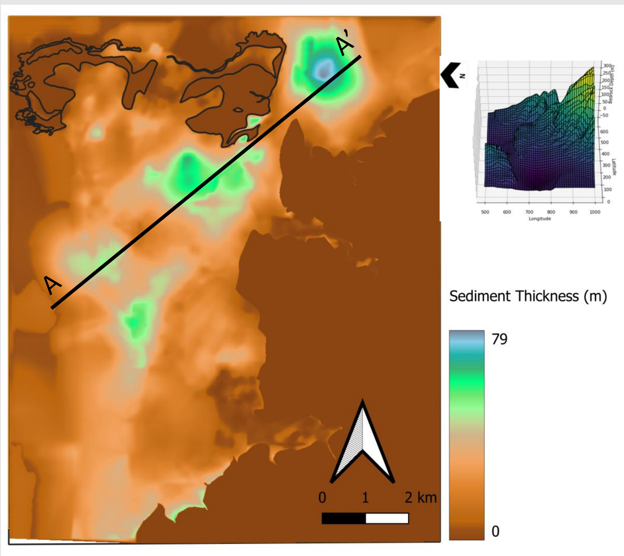


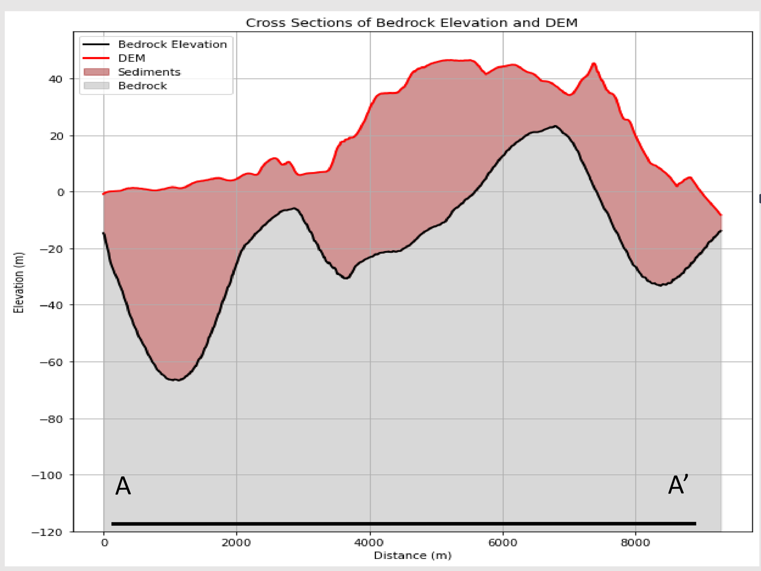
Random Forest at Depth 2: A closer look at the initial decision-making layers of the Random Forest, showcasing the primary features 'DC', 'XX', and 'YY' utilized in early prediction branching, where 'DC' measures proximity to the coastline, and 'XX' and 'YY' represent UTM36N spatial coordinates.



Predicted vs. Actual Bedrock Elevation Scatter Plot: This plot demonstrates a strong linear correlation between the model's predictions and actual bedrock elevations, underscoring the Random Forest model's precision and the fidelity of its predictions.

3D Model Visualizations

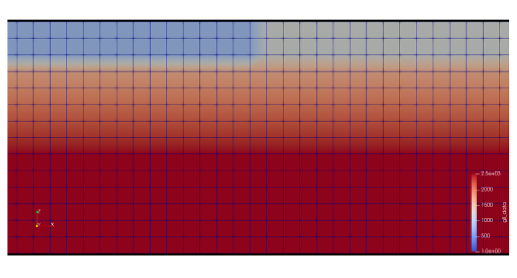




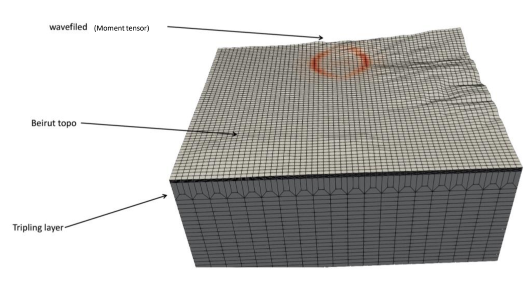
Strategic Implementation of Planewave (PW) in SPECFEM3D Seismic Simulation

Meshing Technique

This simulation employs a non-honoring hexahedral mesh that bypasses strict alignment with geological discontinuities, optimizing for computational efficiency without compromising accuracy



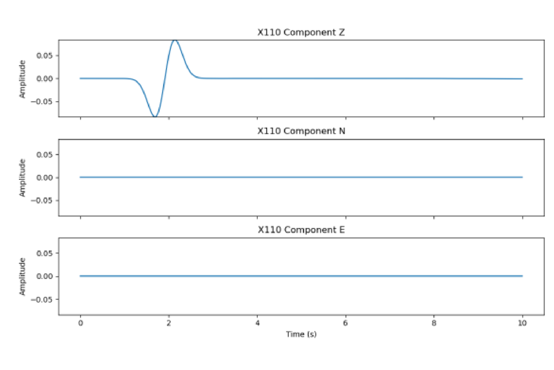
Non-honoring meshing technique

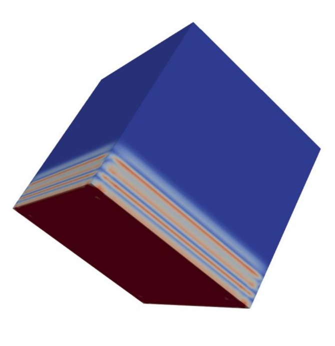


3D mesh of Beirut

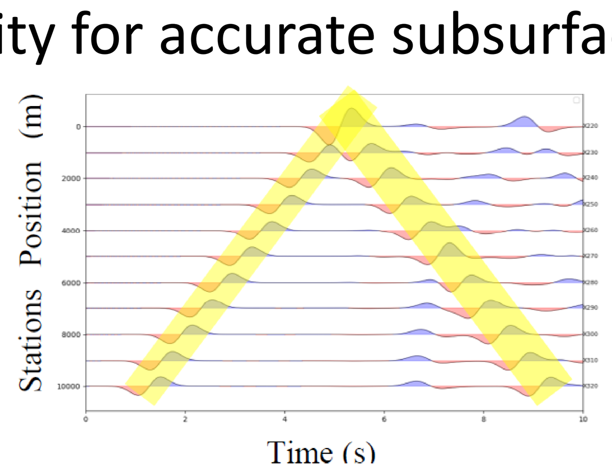
Artifact Mitigation in PW Seismic Simulations

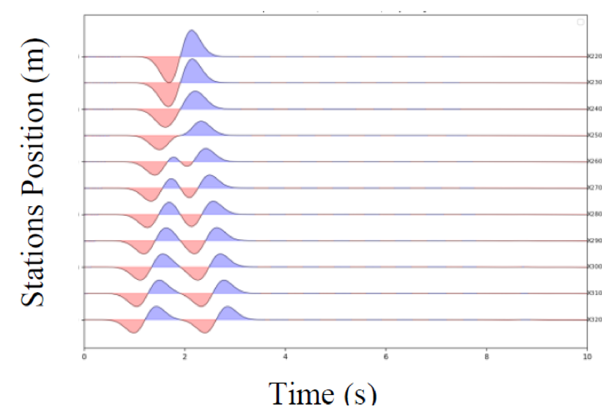
By extending model boundaries, adjusting source depth, and modifying Vs values, artifacts were delayed, preserving the initial data integrity for accurate subsurface interpretation.





PWs are initially approximated using a series of single forces, expressed as Ricker wavelets with a central frequency of 1Hz, propagating vertically in the Z direction from predetermined depths placed on mesh and GLL points.





Initial simulations at a 9800m source depth (Vs=1800m/s, 1Hz frequency) revealed artifacts beyond expected results, shown as deviations from the yellow shaded areas. Adjustments to a shallower 1000m source and a reduced Vs of 1000m/s mitigated these discrepancies, aligning the outcomes with anticipated seismic behaviors and enhancing the clarity of the Z component seismic data.