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USE OF 3D GROUND MOTION SIMULATIONS OF MEGATHRUST EARTHQUAKES IN CHILE TO ENHANCE CATASTROPHE RISK MODELLING FOR (RE)INSURANCE APPLICATIONS

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Abstract: *Chile is home to the largest historical earthquake ever recorded, the May 22 1960 M9.5 Valdivia megathrust event and, among others, the more recent 27 February 2010 M8.8 Maule earthquake that caused significant damage in urban areas, including Santiago. In fact, seismic hazard, resulting damage and losses in Chile are driven by megathrust events in the subduction zone, where the Nazca tectonic plate collides with the South America tectonic plate. Ground shaking and loss estimation in catastrophe models conventionally relies on regression of empirical ground motion recordings (Ground Motion Prediction Equations, or GMPEs) from historical earthquakes. However, GMPEs tend to produce large uncertainty due to the inherent smoothing, and potential bias in the estimated ground motions, particularly for large, rare events. Since seismic instrumentation in 1960 was insufficient to capture the ground motions from the Valdivia event, and no other historical earthquake of this magnitude has occurred, GMPEs are mostly unconstrained for such large-magnitude events. This study is a collaboration between Gallagher Re, the WTW Research Network and San Diego State University (SDSU) and aims to bridge the gap between academia and industry by presenting a viable alternative to using GMPEs for ground shaking and loss estimation from megathrust events. The study illustrates the use in catastrophe modelling of earthquake footprints developed by SDSU using advanced 3D ground motion simulation techniques for M8.2 to M9.5 megathrust scenarios in the South America subduction zone in Chile.*

Generation, validation and application of a 3D model for Chile subduction zone

Ground motion footprints are directly used in damage estimation. Reliable estimates of the insured losses require the characterisation of the ground shaking and its uncertainty to be as accurate as possible. Seismic waves and the resulting ground motions are strongly sensitive to characteristics of the rupture propagation path and 3D crustal structures that can alter the amplitude and propagation period of waves. In contrast, the techniques in widest usage today instead rely on a grossly simplified rupture geometry, no information on rupture front propagation, and empirical ground motion prediction equations (GMPEs). Here, we explore the impact of such state-of-the-art realizations of megathrust scenarios on insured loss estimation in the Chile subduction zone, in comparison with the tools currently available.

We have constructed and validated a 3D Community Velocity Model (CVM) for physics-based 3D simulations in the Peru-Chile coastal regions between 9°S and 42°S to a depth of 160 km. The CVM is based on the Lawrence Livermore National Laboratories Global 3D surface-wave seismic tomography background model (Simmons et al., 2019), merged with more detailed model features

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including the SLAB 2.0 subduction zone geometry model (Hayes et al., 2018), ambient noise tomography across the central Andes (Ward et al., 2013), and the Santiago de Chile basin model with a modified sediment-bedrock interface (Pilz et al., 2011). In order to avoid artifacts in ground motion simulations smoothing was applied to some of the layer boundaries in the background model. In addition, 1D borehole data from the Concepcion and Viña del Mar areas,

and bathymetry data from GEBCO-2021 are incorporated into the CVM. Finally, a shallow geotechnical layer (GTL) is added using a vertical tapering technique based on V_{s30} values derived from topography and modified according to Santiago basin V_{s30} measurements (Diaz et al., 2022).

We carried out 3D deterministic ground motion simulations in the CVM using the scalable 4thorder accurate finite-difference method AWP-ODC (Cui et al., 2013). First, we validated the CVM against strong motion data and the BC Hydro ground motion prediction equation (Abrahamson et al., 2018) for the 2010 M_w8.8 Maule earthquake. The validation used a kinematic source model consisting of a smooth background slip distribution and high stress-drop subevents (Frankel, 2016), optimizing the GTL parameters, basin depths and Vs30 values in the model. We also applied site effect corrections based on a 1D approach (Day, 1996, Hu et al., 2022), to account for effects of the GTL at the upper hundreds of meters with local shear-wave velocity less than 500 m/s. The simulations provided spectral accelerations (SAs) similar to strong motion records from the Maule event as well GMPEs along coastal areas, albeit with a somewhat faster decay at larger distances for SAs at 0.5s (see Figure 1).

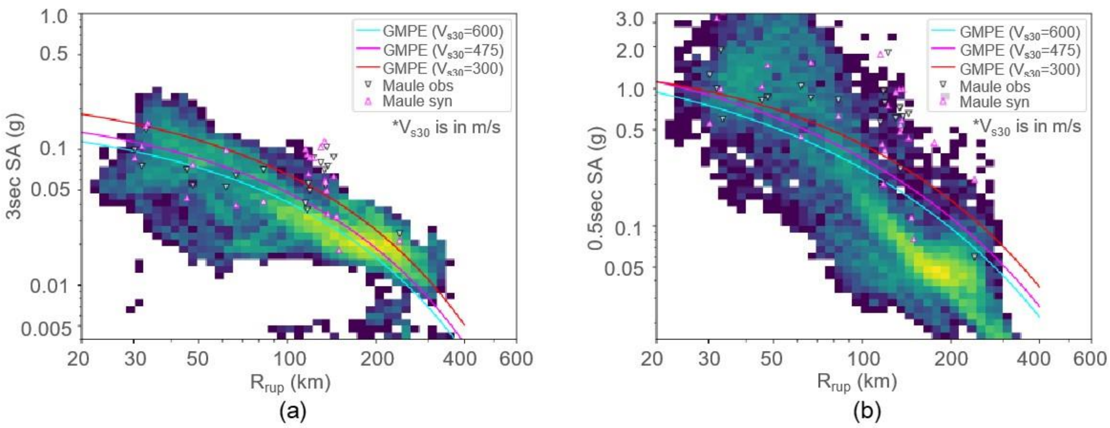

Figure 1. Comparison of SAs (left at 3 sec and right at 0.5 sec) from synthetics, observations and GMPEs for the 2010 Maule event. The color shading shows results from the synthetics across the simulation domain, with higher densities in brighter colors. The black and magenta triangles show the observations and synthetics, respectively, at 25 ground motion stations, and the lines depict values from the BC Hydro GMPE for three different Vs30 values.

The CVM was then used to estimate seismic risk along the south American west coast for 8 megathrust earthquake scenarios ranging from magnitudes 8.2 to 9.5. Figure 2 shows a rupture model and simulated peak ground accelerations (PGAs) for a realization of a 'worst-case' Valdivia-type magnitude 9.5 earthquake scenario, rupturing further to the north compared to the 1960 event, close to metropolitans of Santiago and coastal resort towns. The irregular PGA contours for the predicted PGAs are caused by basin amplification, directional effects, and wave focusing, that are generally insufficiently covered by GMPEs. PGAs in the Santiago area and nearby coastal areas can exceed 0.5g in this scenario.

Comparison of 3D ground motion simulations with catastrophe model footprints

Figure 3 shows a comparison of the 3D simulated ground motion spectral acceleration footprint for the magnitude 9.5 megathrust scenario with the footprint of an equivalent magnitude scenario from a catastrophe model. We find that the GMPEs employed in conventional loss estimation show a much slower decay of the ground shaking with distance which can have a sizeable impact on the loss estimation. Moreover, we find that the Santiago basin significantly amplifies the ground motion, in a way that is poorly captured by the GMPEs.

We tested the loss impact of the footprints on a typical countrywide insured portfolio, comprising mostly of residential and commercial mid to high rise buildings. Around 45% of the portfolio's total insured value is concentrated around Santiago and therefore exposed to spectral accelerations at 1 sec in excess of 0.32g for the magnitude 9.5 scenario in Figure 3. As a simplification for this analysis, we have assumed that the portfolio is entirely comprised of reinforced concrete buildings of the same height having the same vulnerability. To select an appropriate vulnerability curve for this building typology, we leverage the Gallagher Re database of global empirical vulnerability curves. The loss comparison between the 3D simulated and catastrophe model footprints reveals that the differences in loss from the two approaches can be significant with the catastrophe model typically significantly overestimating losses for events with magnitudes above 8.6.

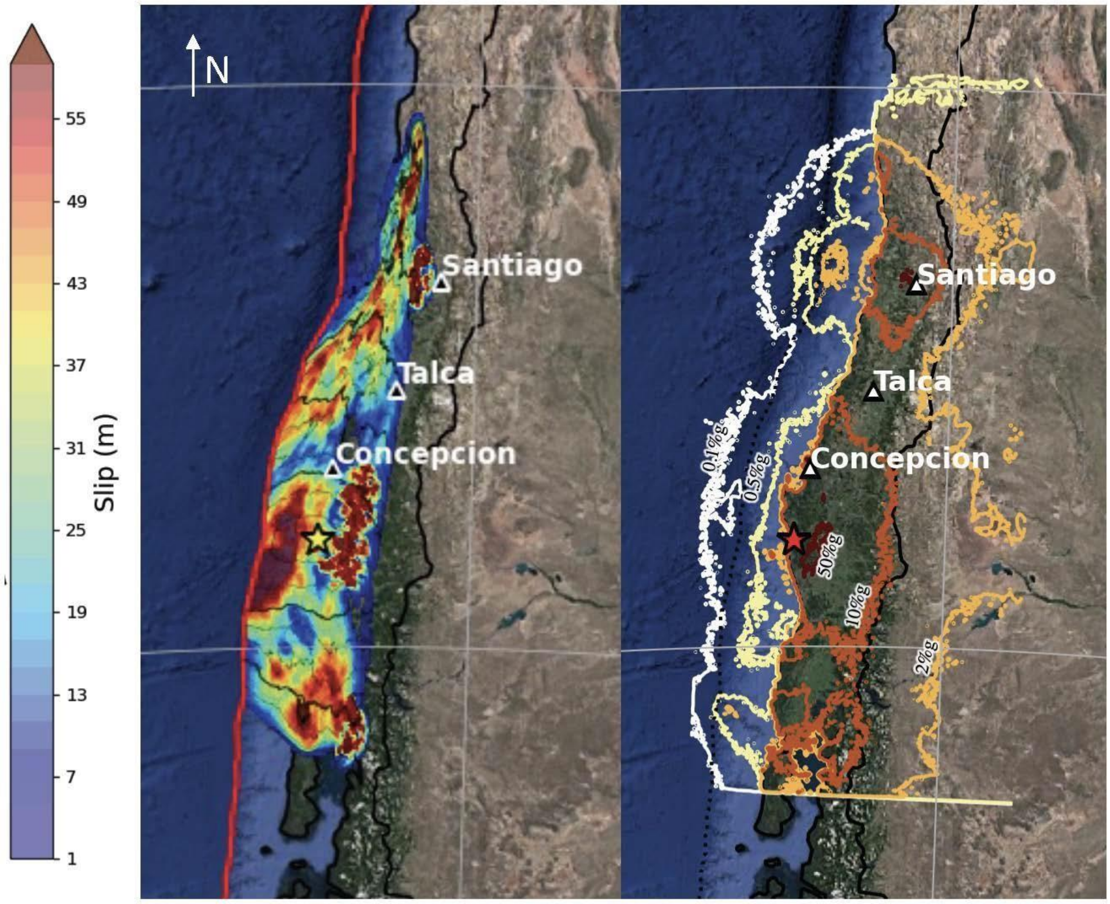

Figure 2. (left) Rupture model and (right) resulting PGAs for a M9.54 megathrust earthquake scenario off the coast of central Chile, where the star depicts the epicenter. The contours show (left) rupture initiation times and (right) peak ground acceleration.

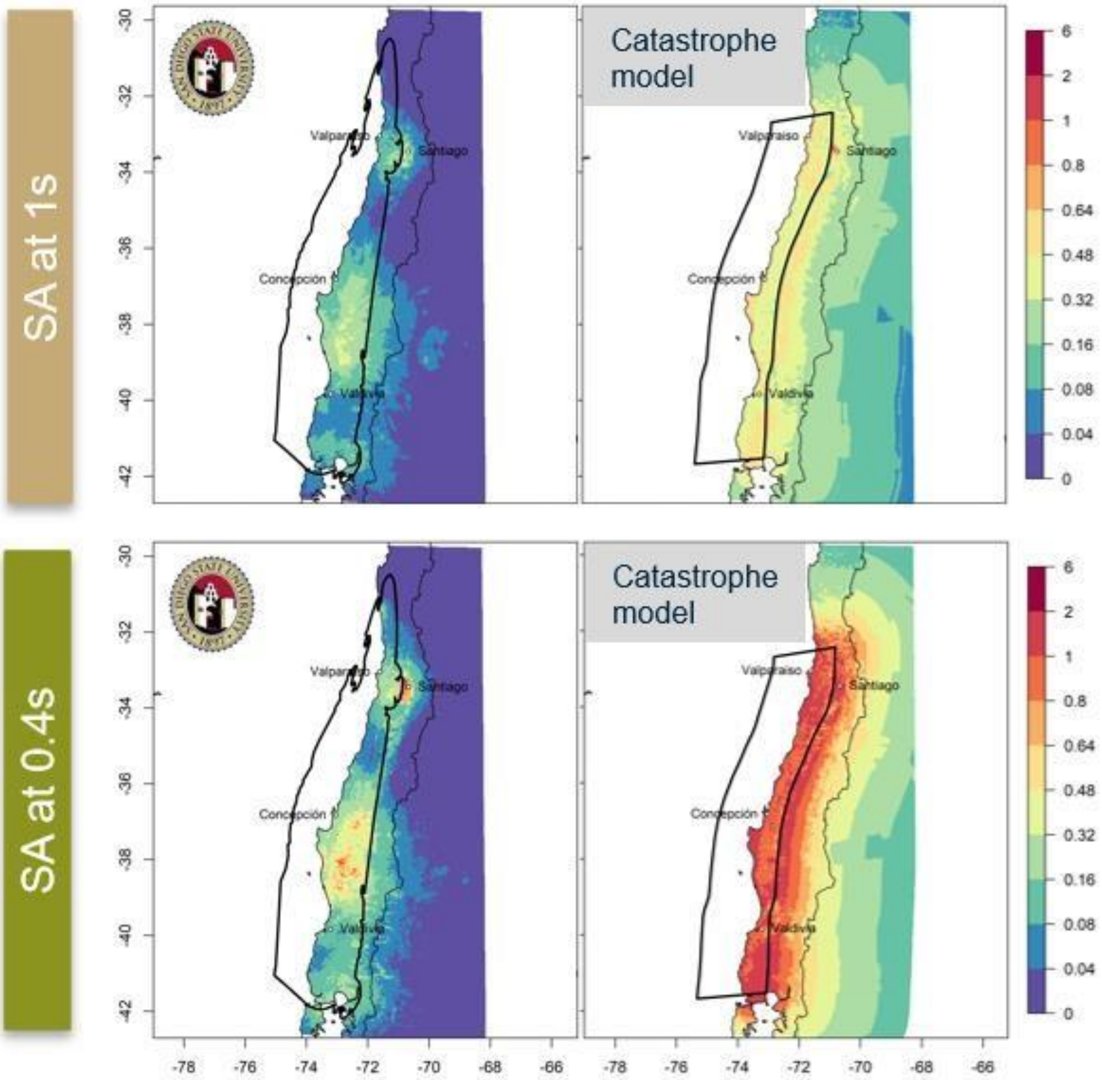

Figure 3. Spectral acceleration at 1sec (top) and 0.4 sec (bottom) in g from a M9.5 scenario predicted by 3D ground motion simulation (left) compared to an equivalent scenario from a catastrophe model (right).

References

Abrahamson N, Kuehn N, Gulerce Z, Gregor N, Bozorgnia Y, Parker G, Stewart J, Chiou B, Idriss I, Campbell K and Youngs R (2018), *Update of the BC Hydro Subduction Ground-Motion Model using the NGA-Subduction Dataset*, PEER Report 2018-02, Pacific Earthquake Engineering Research Center. Technical Report 2018/02, PEER, Berkeley

Cui, Y, Poyraz E, Olsen KB, Zhou J, Withers K, Callaghan S, Larkin J, Guest C, Choi D, Chourasia A, Shi Z, Day SM, Maechling JP and Jordan TH (2013), *Physics-based seismic hazard analysis on petascale heterogeneous supercomputers*, Procs, Supercomputing Conference, 2013

Day SM (1996), RMS Response of a One-Dimensional Half-space to SH, *Bulletin of the Seismological Society of America*, 86(2), 363–370

Diaz J, Saez E, Monsalve M, Candia G, Aron F and Gonzalez G (2022), Machine learning techniques for estimating seismic site amplification in the Santiago basin, Chile, *Engineering Geology*, 306, 106764, doi:http://doi.org/10.1016/j.enggeo.2022.106764
Frankel A (2016), Modeling Strong-Motion Recordings of the 2010 Mw 8.8 Maule, Chile, Earthquake with High Stress-Drop Subevents and Background Slip, *Bulletin of the Seismological Society of America*, 107(1), 372–386, doi:http://doi.org/10.1785/0120160127

GEBCO-2021. https://www.gebco.net/data_and_products/gridded_bathymetry_data/

Hayes GP, Moore GL, Portner DE, Hearne M, Flamme H, Furtney M and Smoczyk GM (2018), Slab2, a comprehensive subduction zone geometry model, *Science*, 362(6410), 58–61, doi:http://doi.org/10.1126/science.aat4723

Hu Z, Olsen KB and Day DM (2022), 0–5 Hz deterministic 3-D ground motion simulations for the 2014 La Habra, California Earthquake, *Geophysical Journal International*, 230(3), 2162–2182

Pilz M, Parolai S, Stupazzini M, Paolucci R and Zschau J (2011), Modelling basin effects on earthquake ground motion in the Santiago de Chile basin by a spectral element code, *Geophysical Journal International*, 187(2), 929–945, doi:http://doi.org/10.1111/j.1365246X.2011.05183.x

Simmons NA, Schuberth BSA, Myers SC and Knapp DR (2019), Resolution and Covariance of the LLNL-G3D-JPS Global Seismic Tomography Model: Applications to Travel time Uncertainty and Tomographic Filtering of Geodynamic Models, *Geophysical Journal International*, 217(3), 1543–1557, doi:http://doi.org/10.1093/gji/ggz102

Ward KM, Porter RC, Zandt G, Beck SL, Wagner LS, Minaya E and Tavera H (2013), Ambient noise tomography across the Central Andes, *Geophysical Journal International*, 194(3), 1559–1573, doi:http://doi.org/10.1093/gji/ggt166