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INVESTIGATING TIME-DEPENDENT EARTHQUAKE CLUSTERING IN SHORT-TERM RISK ANALYSIS

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1. Abstract

The understanding of earthquake occurrence patterns and their implications for short-term increases in seismic hazard and risk is crucial during ongoing seismic crises. This understanding enables informed decision-making by civil protection and governmental agencies. Aftershocks exacerbate seismic hazards by striking already weakened structures and generating strong ground motions, which sometimes surpass the mainshock effects due to their proximity to exposed assets [1–4]. Recent earthquake sequences, e.g., 2010-2011 Canterbury earthquakes (M_w7.1-6.2) in New Zealand, the 2019 Ridgecrest sequence (M_w6.4-7.1) in the US, and the 2023 Turkey earthquakes (M_w7.8-7.5), highlight the significant role of aftershocks in amplifying losses [5,6]. For example, during the Canterbury sequence, several large aftershocks caused greater ground shaking in urban centers than the mainshock, intensifying losses. Thus, for enhancing post-event planning and emergency responses, shifting from time-invariant to time-variant seismic risk estimates is critical. For this, first and foremost, the forecasting capability of time-dependent short-term seismicity clustering models are assessed via retrospective experiments to ensure the model's reliability in estimating the upcoming aftershock sequences in space and time.

The South Iceland Seismic Zone, a prominent transform zone in southwest Iceland, is prone to strong strike-slip earthquakes followed by intense aftershock sequences. The 2008 Ölfus earthquake (M_w 6.3) was the most recent and costliest event in Iceland, triggering substantial aftershock activity. The Hveragerði town, located near the earthquake's epicenter, experienced significant damage to buildings. Elevated hazard levels persisted for days after the mainshock, posing additional challenges for the affected community [7,8].

Our study develops a framework for time-dependent short-term seismic risk assessment for Hveragerði following the 2008 Ölfus earthquake. The short-term probabilistic hazard framework integrates seismicity forecasts from the Bayesian spatiotemporal epidemic-type aftershock sequence (ETAS) model with Iceland-specific hybrid ground motion models (GMMs) [9]. The ETAS model is well-suited for simulating space-time clustering of earthquakes- quantifying triggering rates, spatial distribution, and temporal decay of aftershocks. To investigate elevated seismicity, stochastic simulations of earthquake catalogs are performed corresponding to a set of sampled posteriors of main ETAS parameters. These spatiotemporal forecasts, which account for uncertainty, are compared with actual recorded events exceeding a specified magnitude threshold during the ongoing active sequence.

Bayesian parameter estimation is applied to quantify the uncertainty in the main ETAS model parameters and incorporate them in the resulting forecasts and consequently in the timed-dependent hazard and risk estimates. To do this, we used informative priors obtained from the last intense sequence of June 2000 sequence, enabling improved model calibration [10–12]. By employing an adaptive prior estimation technique, ETAS parameters are continuously updated throughout the sequence as new data

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become available, enhancing forecast reliability during an active seismic sequence. To estimate short-term time-dependent seismic hazard, we calculate the daily probability of exceeding specified PGA thresholds using two Iceland-specific GMMs: a GMM with simplified site term [13] and a detailed geological site term [14]. The results show a sharp increase in PGA exceedance rates early in the sequence. Rea23 predicted higher PGA values than KSea20, emphasizing the importance of considering local site effects, especially in basaltic lava regions.

A detailed building-by-building seismic risk assessment, using high-resolution exposure data for Hveragerði, is conducted to inform post-earthquake decision-making, particularly in small towns with significant exposure near active fault zones. The assessment incorporates uncertainties in building vulnerability models using empirical Bayesian vulnerability models developed for Iceland [15,16]. Building typologies are identified by material, height, and ductility levels following Icelandic design standards. For each building typology, mean damage ratios are estimated, accounting for uncertainties in ETAS-based seismicity forecasts, ground shaking predictions, and vulnerability model parameters. Our findings indicate that buildings with low ductility levels and masonry structures exhibited the highest risk. Masonry buildings, which have historically shown poor resistance to earthquakes, are no longer used in Icelandic construction practices to improve resilience against damaging ground motions. The study highlights the importance of explicitly modeling aftershock clustering and integrating time-dependent seismic hazard and risk assessments for regions with high exposure and vulnerable infrastructure.

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