Session I:
Progress and advances in earthquake source studies

Improvement plan of Active Fault Database of Japan

Takashi AZUMA[1] and Fujika MIYAMOTO[1]

[1] Geological Survey of Japan, AIST, Japan

1. Current version of Active Fault Database of Japan

GSJ/AIST has released Active Fault Database of Japan in 2005, which allows to search data for concern active faults by both ways of on the map and parameter-search system through web system. Currently, it contains fault parameters along with locations and results of surveys by GSJ/AIST and others for 583 fault segments. Fault parameters include length, slip sense, strike, dip-angle of fault plane, slip-rate, average recurrence interval, age of the last faulting event and amount of slip per event. The database also shows probabilities of future faulting event except very short faults (< 10 km in length) or faults with very low activity (< 0.1 m/ky in slip-rate).

2. Map scale and one-click information

Current base map of database shows active fault traces up to ca. 1/200,000 scale. This scale is enough to use map as index of the locations of active fault, but it is rather small to see relationships between active fault trace and architectural structures. In our improvement plan, we will make this scale larger (more precise, ca. 1/50,000 scale), which will be helpful for a construction design and a selection of location near an active fault. Our database includes many of fault parameters, but users need to progress several steps to access them in the current version. We will improve the system to show the important fault parameters, such as slip-rate and amount of slip per event, by one-click on the map.

3. Evaluation of future activities

As mentioned above, our database presents not only fault parameters but also the probabilities of future fault activities for each segment based on results of active fault evaluation. However, the fault segments of very short in length or with very low activity remain of evaluation. We have to seek the new methods of evaluation for such minor active faults. Furthermore, slip-rate of 65 % of all segments are roughly estimated from topographic expression. To calculate them precisely we would like to acquire geological age data of faulted landforms. We have utilized two different processes to calculate probabilities of future faulting events; one is based on renewal process using BPT distribution model and another is calculated by Poisson process. Renewal process requires both of average intervals and age of the last faulting event, whereas Poisson process needs only data of average intervals. Renewal process is very useful to judge the imminentness of a large earthquake in the near future, but it seems difficult to obtain the probability of all segments. Furthermore, it is also too difficult to obtain evidence of average intervals by the geological records of limited number of faulting events in the past, considering temporal variability of fault behavior as have been reported recently. For segments where it is difficult to apply the renewal process, For segments where it is difficult to apply the renewal process, we have promoted to calculate the probability based on Poisson process using average intervals of earthquakes from the geological-based slip-rate and amount of slip per event estimated empirically from length of segments.

NZ NSHM: Seismicity Rate Modelling Overview & Application of the UCERF Inversion Model Method to NZ

Matthew Gerstenberger[1], Russ Van Dissen[1] and the NSHM Team

[1] GNS Science, New Zealand

In 2020 we began the first full revision of the NSHM in 20 years. This revision includes fundamental changes to how we model the spatial and temporal components of earthquake occurrence. We have adopted the UCERF3 “Grand Inversion” recipe and are applying this to the New Zealand fault system. We are also, for the first time, applying the inversion method to develop models for a subduction system; we have developed models for both the Hikurangi-Kermadec system and the Puysegur trench. Using an inversion model allows us to consistently model epistemic uncertainty in earthquake occurrence related to such things as geological estimates of slip rate, geodetic estimates of slip rate, and earthquake catalogue-base expectations of earthquake rates. It also allows us to model many more ruptures and also complex ruptures and to balance their effect on the overall system. To model earthquake occurrence off of known faults, we are using multiple model combinations. The primary model is a “multiplicative-model” combination of smoothed seismicity models, geodetic strain rate, and geological slip-rate information. The model combination is optimised based on performance against the last 70 years of earthquake occurrence in New Zealand. Such catalogue-based models do a poor job of estimating earthquake rates in low-seismicity areas; therefore we supplement the hybrid model with a Uniform Area Zone model where zones are defined based on geodetic strain rates, particularly aiming to model low-seismicity regions well. To account for the greater variability and poorer constraint of rates we have developed a non-Poisson temporal model for these zones. Finally, an overall theme of the model is to account for the epistemic uncertainty in our knowledge of hazard that comes from the non-stationarity of earthquake occurrence. Ultimately this uncertainty makes developing a truly time-independent model impossible and therefore we aim for a forecast time-period of 50-100 years by weighting models based on time-periods for which they are most appropriate.

Earthquake simulation model and seismic hazards for active faults in New Zealand

Bruce E. Shaw[1], Bill Fry[2], Andy Nicol[3], Andy Howell[2,3], Matthew Gerstenberger[2]

[1] Lamont Doherty Earth Observatory, Columbia University, USA

[2] GNS Science, New Zealand

[3] School of Earth and Environment, University of Canterbury, New Zealand

Estimates of earthquake hazards can be impacted by the small and incomplete earthquake datasets available. To address these data issues, in New Zealand we use a physics-based RSQSim simulator engine based on rate-and-state friction equations. We have developed a first-generation model that uses fault sources modified from Stirling et al. (2012) and produces a catalogue of finite ruptures spanning hundreds of thousands of years. Fault interactions and associated triggered events, including interactions between upper-plate faults and the Hikurangi subduction interface, are supported by the model. Statistical analysis indicates that the simulator results are broadly comparable to both historical and geological earthquake observations. In particular, the synthetic catalogue shows substantial variability in the rates and magnitude of earthquakes over instrumental catalogue timescales (e.g., 80 years), and spontaneous multi-fault ruptures of upper crustal faults and the Hikurangi subduction interface. The results highlight the potential to use simulator event sets to develop seismic hazard maps, which could include ground motion models for complex multi-fault ruptures. In addition, the ensemble of large earthquakes provides a range of realistic scenarios that can be used to reduce economic losses and develop civil defence plans for future events expected to impact critical urban areas (e.g., Wellington).

Stirling et al. (2012). National Seismic Hazard Model for New Zealand: 2010 Update. *Bulletin of the Seismological Society of America 102*, 1514-1542, doi:10.1785/0120110170.

Recent progress towards integrating geodetic data and geodetic rates for PSHA in Taiwan

Geng-Pei Lin[1,2], Ray Y. Chuang[1], Kuo-En Ching[3], Wu-Lung Chang[2], Ruey-Juin Rau[4]

[1] Department of Geography, National Taiwan University, Taiwan

[2] Department of Earth Sciences, National Central University, Taiwan

[3] Department of Geomatics, National Cheng Kung University, Taiwan

[4] Department of Earth Sciences, National Cheng Kung University, Taiwan

In the recent decades, rapid development of geodetic approaches has shown great abilities to resolve surface deformation associated with active tectonics through different stages of an earthquake cycle. Geodetic observations provide us opportunities to estimate the characteristics of seismogenic fault behaviors, which could be helpful for seismic hazard assessments. In Taiwan, earth scientists have established dense geodetic arrays of GNSS, leveling since 90's. Together with InSAR observations, the geodetic data has been used for monitoring surface deformation of major earthquakes and interseismic strain accumulation. In this project, therefore, we would like to utilize geodetic observations to help probabilistic seismic hazard assessments (PSHA). There are two major components: (1) integrating geodetic observations for Taiwan, and (2) estimating slip rates and recurrence intervals for Taiwan Earthquake Model (TEM) active structures using the geodetic data. Currently, we are using GNSS and leveling to estimate horizontal and vertical surface velocities, and building time series of surface deformation by using PSInSAR technique. In addition, we are using the GNSS velocities to generate the first version of geodetic rates for the TEM active structures. Moreover, we are testing different methods to calculate an island-wise strain rate map, which will be used to estimate seismicity rates for the PSHA.

Constructing the Offshore Seismogenic Structure Source Database in Taiwan

Cheng-Hung Chen[1], J. Bruce H. Shyu[1]

[1] Department of Geosciences, National Taiwan University, Taiwan

Taiwan is located at an active orogenic belt and prone to earthquake hazards. There are many seismogenic structures and earthquake activities on the island. With proper seismic hazard and risk assessments and preparations before catastrophic earthquakes occur, the losses caused by the disaster would be greatly reduced. As part of the Taiwan Earthquake Model (TEM) Project funded by the Ministry of Science and Technology, Taiwan, our team is working on constructing the seismogenic structure database in Taiwan, including the locations of the structures and to establish the structural parameters, such as earthquake magnitude, long-term slip rate, and recurrence interval. A new version of the database with 45 on-land seismogenic structures has been published in 2020.

However, earthquakes in Taiwan do not only occur on structures on-land, but may also occur on offshore structures. Therefore, the main purpose of this study is to construct the first version of the offshore seismogenic structure database in Taiwan. At present, we have been working on data collection and integration, and 50 offshore structures have been preliminarily identified. In the future, we will integrate previous geological and geophysical results offshore Taiwan to better locate the structures and to determine their subsurface geometries and their activity. With these information, we would be able to calculate the structural parameters to facilitate earthquake magnitude and probability calculations to provide better constraints for future seismic hazard assessment and hazard mitigation studies.

Session II:
Progress and advances in ground motion studies

Ground Motion Characterization Model Overview for the 2022 NZ NSHM Update

Robin Lee[1], Brendon Bradley[1], Jesse Hutchinson[1], Elena Manea[2]

[1] University of Canterbury, New Zealand

[2] GNS Science, New Zealand

As a part of the ongoing 2022 NZ National Seismic Hazard Model Update, several activities have been included to implement and apply the best available science within ground motion characterisation modelling. In particular, a comprehensive ground motion database as been developed, existing empirical ground motion models have been evaluated, and backbone ground motion model development is ongoing.

The ground motion database collects and presents information on earthquake ground motions and their related source, site, and record metadata. The data, obtained from numerous different sources with variable quality, are synthesized and harmonized with associated uncertainties or quality scores. The database has many applications such as ground motion model evaluation and development, and direct use in engineering applications. Current and future work will improve the database through earthquake relocations, better magnitude and focal mechanism characterisation, and more site investigations.

The predictive capability of candidate empirical ground motion models are evaluated to ascertain models which provide good prediction for NZ conditions and adequately capture epistemic uncertainty. A smaller high-quality subset of the ground motion database appropriate for ground motion model validation was adopted comprising over 15000 ground motion records from over 800 earthquakes recorded at 350 strong motion stations. Prediction of ground motions from shallow crustal, subduction interface and subduction slab earthquakes are considered. Numerous candidate models are considered from Next Generation Attenuation studies (e.g., NGA-West2 and NGA-Sub), as well as other recent international and NZ-specific studies. Assessment of model prediction bias and standard deviations are presented to provide a summary of model performance, as well as analysis of source, path and site parameter dependence and spatial trends. Lastly, an examination of prediction for scenarios beyond the validation data range (e.g., large Mw subduction interface) is undertaken, including a comparison between models for such scenarios. Results from this study are used to inform ground motion modelling decisions in seismic hazard analyses, such as logic tree weights.

Backbone modelling efforts are also underway using a range of development methodologies. One backbone model will be developed through the use of weighted ensembles of existing ground motion models, as informed by the evaluation of existing empirical ground motion models. Two more backbone models will be developed through the use of target region (NZ) modifications to host models as informed through Fourier amplitude spectra analyses of observed ground motions.

Capturing local ground motions in seismic hazard: the Wellington basin case study

Anna Kaiser[1], Matt Hill[1], Liam Wotherspoon[2], Robin Lee[2], Elena Manea[1], Chris de la Torre[3], Brendon Bradley[3], Matt Gerstenberger[1]

[1] GNS Science, Lower Hutt, New Zealand

[2] University of Canterbury, Christchurch, New Zealand

[3] University of Auckland, New Zealand

A challenge for the seismological community is the treatment of local site/basin effects in urban seismic hazard analysis. New global ground motion models (GMMs) have been shown to perform well overall in New Zealand, forming a robust foundation for the national seismic hazard model (NSHM). However, it is widely recognised that the treatment of site response based on a single site metric of Vs30 is limited.

To further the goal of more fully capturing site/basin amplification in future interations of NSHM, the programme is (i) improving the available national strong motion station metadata at strong motion stations to test and develop ground motion models for the future, and (ii) using a Wellington basin case study to apply empirical and physics-based non-ergodic modelling techniques, to quantify site/basin amplification and its uncertainty.

We will present an overview of the work in progress, including the new compilation of site metadata. This has been used to examine mean station residuals relative to global GMMs for New Zealand basins, including Wellington. In Wellington, we also have developed a new a regional basin velocity model for Wellington, with first simulation results using the Graves & Pitarka (2010) method. These methods are complemented by site-specific nonlinear site response analyses to investigate the influence of the near-surface soils.

Observation of frequency-dependent nonlinear damping ratio for near-surface sediments

Chun-Hsiang Kuo[1,2,3], Jyun-Yan Huang[3], Che-Min Lin[3], Chun-Te Chen[4], and Kuo-Liang Wen[1,3]

[1] Department of Earth Sciences, National Central University, Taiwan

[2] Earthquake-Disaster & Risk Evaluation and Management Center, National Central University, Taiwan

[3] National Center for Research on Earthquake Engineering, Taiwan

[4] Institute of Earth Sciences, Academia Sinica, Taiwan

The damping ratio is an important index used in soil nonlinearity studies and is mostly proportional to the shear strain increase. Previous researches indicated a frequency-independent damping in most cases. In this study, frequency-dependent damping was introduced from frequency-dependent Q calculated through the spectral ratio method of near-surface structures using the power spectrum of strong motion records in the Strong Motion Array in Taiwan Phase I (SMART1). The dense SMART1 recorded significant strong motions in the 1980s, which can be used to identify soil nonlinearity at near surfaces. A 40%–50% increase in frequency-dependent damping for SMART1 was identified, with strain increasing from 0.01% to 0.1% in near-surface regions. A large damping was also found in the shallow sediments with mean Vs below 600 m/s on the topmost 500 m layers in the SMART1 database at a frequency range of 3–8 Hz, which is independent of the magnitude scaling or near-field travel distance scaling relations.

Toward Single-Path Ground Motion Prediction Equation

Jia-Cian Gao[1,2]

[1] Earthquake-Disaster & Risk Evaluation and Management Center (E-DREaM), National Central University, Taiwan

[2] Graduate Institute of Applied Geology, National Central University, Taiwan

Obtaining ground-motion prediction equations (GMPEs) are based on datasets of ground-motion parameters of different earthquakes in worldwide by the ergodic hypothesis. It causes excessive variability that leads to overestimation of seismic hazard levels. Some regional GMPEs (e.g., Lin et al., 2011; Lin and Lee, 2008) were obtained based on only Taiwan dataset that catch the ground motion mean value precisely and lower ground motion variability, if the entire uncertainty in regressions is treated as aleatory uncertainty when a significant fraction of it is really epistemic. Sung and Lee (2016) has proposed a method, named the path diagram, to quantify systematic path effects on ground-motion variability to know the size of aleatory in Taiwan. Besides, Sung and Lee (2019) has proposed the single-station attenuation model by non-ergodic hypothesis established from the recordings of a single station. Based on this model, site-to-site variability can be ignored. Due to the availability of data, however, the approach is not applicable to engineering purposes. To overcome such difficulty, Gao et al. (2021) has proposed a novel approach to construct site-dependent GMPEs. This innovation minimizes the GMPE uncertainties to avoid over-estimations in a probabilistic seismic hazard analysis. In addition, the source zones are involved in GMPEs to distinguish the source uncertainty, that could precisely assess the seismic hazard.

Toward construction of strong-motion database for seismic hazard assessment in Japan

Asako Iwaki[1], Nobuyuki Morikawa[1], Hiroyuki Fujiwara[1]

[1] National Research Institute for Earth Science and Disaster Resilience (NIED), Japan

In Japan, strong motion observation has been conducted for nearly 70 years now. A huge amount of strong motion observation data has been collected by many institutions and companies, including more than 800,000 records by K-NET and KiK-net of NIED. Using the accumulated observation data, a number of ground-motion prediction models (GMPEs) have been constructed by regression analysis, which have been played an essential role in seismic hazard assessment. Japanese GMPEs have been constructed by many research groups basically using their own varying datasets and conditions; however, in order to appropriately evaluate the performance and epistemic uncertainty among multiple GMPEs, it is necessary to have datasets and other conditions in common. It has been also pointed out that current GMPEs are not sufficiently accurate at predicting ground motion with low probability, such as near-fault ground motion and ground motion from mega-earthquakes. To solve these problems, our group has started a project to construct a unified and expanded strong-motion database, aiming to construct data-driven GMPEs and improve current PSHA in Japan.

Currently we have constructed a prototype of the unified strong motion database from all K-NET and KiK-net strong-motion records. The database consists of three files: seismic source, site, and strong-motion files. The seismic source file contains the earthquake information such as origin times and hypocenter locations by JMA, the moment tensor solutions by F-net, etc. The site file contains the information of the observation sites as well as the parameters for site characteristics such as VS30. The strong-motion file contains the indices such as PGA, PGV, acceleration response spectra, etc.

In addition, we plan to utilize the ground-motion simulation data to make up for the deficiency of the observation database especially in short distances and large magnitudes. Here, we use numerical simulations based on fault and wave-propagation models, often called physics-based simulation (PBS), which can consider the effects of rupture propagation and wave propagation through complicated tectonics. We attempt to merge PBS data with observation data in the same format to enlarge the database. Using the PBS data for the scenario active fault earthquakes in the National Seismic Hazard Map, we performed statistical analysis to ensure the PBS data provide stable ground motion level and appropriate variability of ground motion.

Ground Motion Predictions Using Machine Learning Methods

Tomohisa OKAZAKI[1]

[1] RIKEN Center for Advanced Intelligence Project, Japan

I will present our recent studies to improve ground motion predictions using machine learning methods.

The first topic is broadband ground-motion simulations for scenario earthquakes [1]. Hybrid approaches combine long-period and short-period waveforms obtained from different models, which can lead to incompatible time histories and frequency properties. We explore a machine learning model that converts long-period waveforms to short-period waveforms in order to ensure the consistency between long-period and short-period components. Critical features are (1) the similarity of acceleration envelopes is measured by the Wasserstein distance, which captures the global properties of waveforms, (2) the construction of a latent space by simultaneously embedding long-period and short-period waveforms using an extension of t-SNE, and (3) the interpolation of desired short-period waveforms using a notion of the Wasserstein barycenter.

The second topic deals with empirical ground motion models (GMMs) using artificial neural networks (ANNs). First, we indicate that when site-condition proxies such as VS30 are used as input variables, observational sites must be separated in training and validation datasets to properly evaluate the generalization performance of GMMs [2]. This forces to reconsider the validity of existing data-driven GMMs. We then propose the use of monotonic neural networks to maintain generalization performance of flexible data-driven GMMs. Second, we construct a site-specific GMM using ANNs [3], and demonstrate that the one-hot representation of site labels makes the best use of flexibility of ANNs to obtain site-specific properties while suppressing overfitting at sites with few observational records.

[1] Okazaki, T., H. Hachiya, A. Iwaki, T. Maeda, H. Fujiwara, N. Ueda (2021). Broad-band ground motions with consistent long-period and short-period components using Wasserstein interpolation of acceleration envelopes, *Geophysical Journal International*, **227**(1), 333–349.

[2] Okazaki, T., N. Morikawa, H. Fujiwara, N. Ueda (2021). Monotonic Neural Network for Ground-Motion Predictions to Avoid Overfitting to Recorded Sites, *Seismological Research Letters*, **92**(6), 3552–3564.

[3] Okazaki, T., N. Morikawa, A. Iwaki, H. Fujiwara, T. Iwata, N. Ueda (2021). Ground-Motion Prediction Model Based on Neural Networks to Extract Site Properties from Observational Records, *Bulletin of the Seismological Society of America*, **111**(4), 1740–1753.

Session III:

Progress and applications of national earthquake hazard models

Validation of the probabilistic seismic hazard assessment by the Taiwan Earthquake Model: Comparison with strong ground motion observations

Chung-Han Chan[1]

[1] Earthquake-Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, Taiwan

To assess the seismic hazard for Taiwan, we implemented the strong ground motion observations and the probabilistic hazard model proposed by the Taiwan earthquake model (TEM). We accessed the Taiwan Strong Motion Instrumentation Program (TSMIP) database and reported the maximum ground shaking of each strong-motion station. Comparing the TSMIP observations and the TEM hazard model reveals similar spatial patterns in which 303 of 536 (56.5%) stations differ by less than 0.1 g. However, some records indicate significantly higher shaking levels than the model does due to the occurrence of some large events, for example, the 1999 Mw7.6 Chi-Chi earthquake. Such discrepancies cannot be explained by model parameter uncertainties but by unexpected events in the given short observation period. We have confirmed that although each seismogenic structure in Taiwan is unlikely to rupture within a short period, summarized earthquake potentials from all the structures are significant. The outcomes of this study provide not only crucial information to urban planning on a city scale and building code legislation on a national scale, but also suggestions to the next generation of probabilistic seismic hazard assessment for Taiwan as well as other regions.

Perspectives of TEM PSHA

Kuo-Fong Ma[1,2]

[1] Taiwan Earthquake Research Center (TEC), Institute of Earth Sciences, Academia Sinica, Taiwan

[2] Earthquake – Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, Taiwan

Despite the high-seismicity and subsequent historically damaging earthquakes, no official NSHM was made prior to the publication of the Taiwan Earthquake Model (TEM) in 2015 by Wang, Chan, et al. (2016), TEM PSHA2015, now proceed to TEM PSHA2020 Chan et al., (2020). TEM continues the effort to improve the understanding of probabilistic seismic hazard and risk assessment by integrating the earthquake science, earthquake engineering, and social science communities of Taiwan. Till now, the TEM PSHA is not yet directly applied into the Taiwan building codes; however, it influences decision making by government agencies in deciding policies on natural hazard disaster prevention, annual earthquake drills, and partially in building code, and retrofit policies. Most significant impact is the attention from industrial partners and government funding agencies for research and product directions to bringing important outputs/inputs into societal decision making. To view the current status of TEM PSHA, the contributions could be seen from three aspects, 1, to present as a scientific platform, which evolving the progressive of scientific studies; 2. to act as a conversational platform, which improving the dialogs among scientists, engineers, and government agencies; 3. to present as an educational platform, which providing the rational judgments to face the natural hazard and risk. With new development in this digital era of 21st century, our government urgently encourages the digital transformation of disaster prevention and rescue, the annual earthquake drills since 2019 based on TEM PSHA becomes a possible pilot exercise to this task force. We appreciate the continuing collaborative work of Taiwan-Japan-New Zealand, which help to strengthen TEM PSHA despite the remaining challenges in the development of science-driven models, quantifying the uncertainties, and the development of a proper testing phase of the model to quantify its consistency and skill as stated in Reviews of Geophysics by Gerstenberger et al. (2021).

The 2020 version of National Seismic Hazard Maps for Japan

N. Morikawa[1], H. Fujiwara[1], S. Senna[1], T. Maeda[1], A. Iwaki[1], S. Kawai[1]

[1] National Research Institute for Earth Science and Disaster Resilience, Japan

Based on the lessons learned from the 2011 great Tohoku earthquake, the seismic activity model in National Seismic Hazard Maps for Japan has significantly updated in 2014. After that, minor changes have been applied in 2016, 2017 and 2018 based on new "long-term evaluation" for earthquakes in major active faults or subduction-zone earthquakes. The 2020 version of National Seismic Hazard Maps for Japan was published in March 2021 with major model updates.

Among the updates on the seismic activity model, the diversity of the source regions was further considered in the 2020 version for the models of huge subduction inter-plate earthquakes. For huge earthquakes that occur along the Nankai Trough, the model of 15 occurrence patterns consisting of 15 source regions (Mw 8.2-9.1) was changed to the model of 177 occurrence patterns consisting of 80 source regions (Mw 7.6-9.1). For the back ground earthquakes model, the region classification in the "regional method" was updated including additions, and the frequency of earthquake occurrence was calculated using the earthquake catalog by Japan Meteorological Agency until 2017, which includes the aftershocks of the 2011 great Tohoku earthquake.

Regarding the ground motion evaluation model, the nation-wide geomorphological engineering classification map was updated, and the average S-wave velocity up to 30 m depth (Vs30) was also updated (Wakamatsu and Matsuoka, 2020). For Kanto district, a newly constructed underground structure model from seismic bedrock to ground surface was applied. With these new underground structure models, not only probabilistic seismic hazard maps but also scenario earthquake shaking maps has been updated.

We also made a nation-wide seismic hazard map for peak acceleration by using the seismic activity model in the 2020 version and ground motion prediction equation by Morikawa and Fujiwara (2013). In addition, we conducted seismic hazard assessments using acceleration response spectra for the purpose of promoting engineering use of the National Seismic Hazard Maps for Japan. We will publish these results through J-SHIS in the near future.

Regarding the modeling of background earthquakes, how to treat aftershock activity of mega-earthquakes such as the great Tohoku earthquake, and how to develop an earthquake catalog for marginal regions of Japan are major issues in the future. On the other hand, it is necessary to construct a framework that can take into account the epistemic uncertainties for the application of ground motion models to mega-earthquakes or near-fault area, where observation records are insufficient. In order to solve these issues, it is very important to collaborate with other countries and share not only knowledge on seismic hazard assessment but also fundamental data such as earthquake catalogs and strong-motion records.

NSHM 2022 Revision Project Overview and Uptake to Building Codes

Matthew Gerstenberger[1] and the NSHM Team

[1] GNS Science, New Zealand

In 2020 we began the first full revision of the NSHM in 20 years. This revision includes fundamental changes to all parts of the model. In parallel to the revision, MBIE, the New Zealand government agency in charge of the Building Code, has begun a process to critically rethink how NSHM estimates are used to meet policy needs. We are working closely with this process.

An important part of our revision is the use of participatory review through an active Technical Advisory Group; many of whom are engaged on a weekly basis. Working with this group, last year we established a set of model priorities. Key amongst these, and also expected by MBIE, is a significant focus on modelling epistemic uncertainty across the model. A goal is to provide and communicate this uncertainty in ways that are digestible by the engineering community, government policy makers and the insurance community. Capturing this uncertainty allows end-users to understand our confidence in any particular result. Other key goals are to: 1) use the UCERF3 Grand Inversion recipe to allow for complex multi-fault ruptures, reduced reliance on strict segmentation and for coherent modelling of epistemic uncertainty; 2) use of more statistically rigorous distributed seismicity models, including specific modelling for increased variability in low-seismicity regions; 3) development of regionalised backbone ground motion models; and 4) modelling of basin amplification for the Wellington region. We aim to have the new model completed by August 2022.

NSHM 2022 Products and End-User Engagement

Chris DiCaprio[1]

[1] GNS Science, New Zealand

A key deliverable of the National Seismic Hazard Model Revision is an online dissemination service (webapp) for use by a range of technical end users including geotechnical engineers, structural engineers, building code advisors, and insurance risk analysts. Each end user group has different needs for the NSHM and requires different output products from the model. In order to define output requirements and the manner in which users would interact with the dissemination service we held workshops with representatives of the various end user groups. In these workshops we developed user personas and user stories that were used as the basis for the output set and user experience (UX) design. A beta version of the webapp is planned for early 2022 for testing and feedback from end-user representatives. Feedback from the testing phase will be used to make improvements for the public launch of the site in August, 2022.

Session IV-a:

Short presentations

Fault-network inversions of geologic and geodetic data for regional seismic hazard analysis

Richard Styron[1], Thomas Chartier[1], Marco Pagani[1]

[1] GEM Foundation, Italy

A fundamental challenge in Probabilistic Seismic Hazard Analysis (PSHA) is that the rates of earthquake generation from seismic sources are unknown, and are not currently measurable. Most modern PSHA methods consider the rates of earthquake generation on a fault to be proportional to the slip rate of the fault, which can be measured; however, the slip rates of most faults of seismic consequence have not been measured or otherwise formally estimated, because of the great effort required. The most promising method for efficiently estimating the slip rates of all faults in a region of interest is through a joint inversion of geologic and geodetic data. Such an inversion yields internally-consistent slip rates for all faults in a region, using both fault-specific geologic slip rates where available, which provide tight constraints on individual structures without providing information on regional or integrated deformation, and geodetic data, which does not necessarily constrain individual fault slip rates but quantifies the regional deformation field and strain budget. Joint inversions of these two data types leverages the strengths of each to compensate for the weaknesses of the other. In this way, these inversions that integrate both local and regional deformation data are best thought of as 'fault network inversions'.

The Global Earthquake Model Foundation (GEM) has recently made great headway in fault network inversions to create seismic source models for regional PSHA using a block (tectonic microplate) model, and has successfully used the methods to create high-accuracy PSHA models in tectonically complex regions. This process involves three main steps. The first is a re-mapping of active faults in the region synchronously with the mapping of the blocks. Faults are mapped based on previous mapping, tectonic geomorphology and seismicity, at a target resolution of about 1:100,000, though this can vary locally. Blocks are mapped with the faults to ensure maximum compatibility. Then, geologic and geodetic data are assembled and inverted to find the relative motions of all blocks (which translate to fault slip rates), as well as spatially-variable strain accumulation rates on subduction zones if present in the region, using GEM's new Oiler block modeling code. Finally, the rates of earthquake occurrence are found for all faults as well as off-fault areas using the Sherifs program, which models sub- to multi-fault ruptures (relaxing fault segmentation assumptions) and off-fault seismicity using fault geometries, slip rates, and instrumental earthquake catalogs to constrain the regional magnitude-frequency distribution. This workflow greatly reduces subjective "expert judgement" estimations and allows for a very integrated and seamless pipeline from fault mapping through hazard analysis.

The first complete use of this workflow was the construction of GEM's new PSHA model for mainland China and the vicinity (including the Himalaya, Tien Shan and Pamir). The block model involves approximately 1000 faults separating 300 blocks, with rates constrained by over 150 Quaternary geologic slip rates and over 3000 GNSS velocity vectors. This study may have the first slip rate estimations for hundreds of faults in the model. The resulting hazard model has much higher hazard localized on faults than previous assessments, particularly for under-studied faults in complex orogenic settings, where short and incomplete instrumental seismic catalogs were not capable of fully characterizing earthquake occurrence.

GEM is currently expanding the model coverage to much of Asia and North America, to produce national to subcontinental-scale hazard models that are well integrated.

Constraining the Rates of Large, Moderate and Small Earthquakes in New Zealand for the 2022 National Seismic Hazard Model

Chris Rollins[1], Matt Gerstenberger[1], Annemarie Christophersen[1], Kiran Kumar Thingbaijam[1] and Russ Van Dissen[1]

[1] GNS Science, Lower Hutt, New Zealand

The 2022 New Zealand National Seismic Hazard Model (NSHM) consists of three layers: a Seismicity Rate Model (SRM), which describes the occurrence rates of earthquakes of various sizes throughout New Zealand; a Ground Motion Characterisation Model, which describes how those earthquakes will shake the ground; and an uncertainty model, describing the uncertainty in both components and how they are put together. The SRM itself consists of several components. On the Hikurangi-Kermadec and Puysegur-Fiordland subduction zones, the SRM is a “grand inversion” [Page et al., 2014; Field et al., 2014] that solves for the rates of earthquake ruptures at various locations along the subduction interfaces, subject to several constraints. One of these constraints is that the rates at each magnitude must sum to a total prescribed magnitude-frequency distribution (MFD) (within some uncertainty). For crustal earthquakes, we use a grand inversion to solve for the rates of ruptures on known active faults, including a crustal MFD constraint. To characterize the likelihoods of earthquakes not on known faults, we also use two distributed seismicity models scaled up to a prescribed MFD. The crustal SRM is then a blend of the on-fault and distributed seismicity models.

The total magnitude-frequency distribution of earthquakes is therefore a crucial constraint within the SRM and the NSHM as a whole. To compute the crustal MFD, we use the instrumental earthquake catalogue in New Zealand accounting for magnitude corrections; earthquake depths and their uncertainties (and those of subduction interfaces); heterogeneity introduced by the Taupo Volcanic Zone (TVZ); and variability in earthquake rates through time. For the Hikurangi-Kermadec interface, we use the earthquake catalogue of Heuret et al. [2011] and Marzocchi et al. [2016], as well as a global subduction MFD scaled down to the length of the Hikurangi-Kermadec arc. For the Puysegur interface, we use both the magnitude-corrected NZ catalogue and the scaled-down global subduction constraint.

Earthquake Timings and Fault Interactions in Central New Zealand

Jade Humphrey[1], Andy Nicol[1], Andy Howell[1,2], Nicola Litchfield[2], Russ Van Dissen[2], Rob Langridge[2]

[1] School of Earth and Environment, University of Canterbury, Christchurch, New Zealand

[2] GNS Science, Lower Hutt, New Zealand.

Earthquake records currently used to forecast the timing and magnitude of future earthquakes are relatively short and often incomplete. RSQSim synthetic earthquake catalogues have been developed for New Zealand to help address this data issue and improve seismic hazard assessment. To evaluate how well the synthetic earthquake model is replicating fault behaviour, we are running tests comparing the spatial and temporal distributions of paleoearthquakes and synthetic earthquakes from central New Zealand. We are applying Bayesian statistics to fault trench data to quantify the probability that large earthquakes in central New Zealand occurred synchronously between different faults and segments along the same fault. These techniques utilise >150 radiocarbon dates and allow for more robust comparisons of paleoearthquake timing.

The refined data improves estimates of the timing of paleoearthquakes for the faults studied. These new ages indicate that in some cases, the timings of surface-rupturing earthquakes vary, while in others they are approximately the same age, suggesting interactions across the fault system. These 'synchronous' earthquakes occurred during time windows of up to 150 years, with the most striking event recorded on the Wellington, Wairarapa and subduction thrust faults at approximately 700-850 cal. yr BP. The apparent synchroneity of earthquakes could indicate the occurrence of large multi-fault ruptures and/or earthquake clusters, both of which may suggest stress transfer and interactions between faults on timescales of seconds to hundreds of years. Our analysis provides support for the complex ruptures observed in physics-based earthquake modelling. These models and paleoearthquake data highlight the importance of fault interactions for seismic hazard and improved resilience to large future earthquakes in central New Zealand.

Structural monitoring in Wellington using regional earthquakes

Caroline Holden[1]

[1] SeismoCity Ltd, New Zealand

Sklodowska et al. (2021) employed advanced seismological techniques usually applied to Earth studies to the Te Puni building (instrumented as part of the GeoNet building instrumentation programme) for the 2009-2017 time-period. Focusing on two techniques (Interferometry and transfer function), we were able to track transient changes in the building dynamic response from various level of earthquake loadings and over time despite the absence of structural damage.

Learning from this project, we apply the above techniques to buildings from the GeoNet building instrumentation programme with a different service function, or different typology than the Te Puni steel structure.

MBIE Stout street is an interesting example of a 1920s concrete structure with heavy steel reinforcing and of government level importance. Instrumentation of the building started in 2014. We selected a total of over 3,000 earthquakes from 2014 to 2021. Early results already show a clear decrease in the fondamental frequency of the structure in a step change trend related to the Kaikoura earthquake. We are working with the engineering team who designed the strengthening phase of this structure in 2014 to discuss the interpretation of these results and interest in expanding this research to other parts of the building.

The Wellington hospital, a modern base-isolated structure is also an ideal candidate showcasing damage avoidance system and with a high importance level. Instrumentation of the building started in 2009. We selected a total of 903 earthquakes from 2009 to 2021. Early results already show a clear decrease in the fundamental frequency of the structure in a step change trend, occurring following the 2013 Cook Strait sequence and the 2016 M7.8 Kaikoura earthquake. This analysis is specifically related to one direction of the building and more detailed analysis is currently being done.

Testing and Evaluation of Earthquake Rupture Simulations for New Zealand

Govinda P. Niroula[1], Mark W. Stirling[1], Matthew Gerstenberger[2]

[1] Department of Geology, University of Otago, New Zealand

[2] GNS Science, New Zealand

We provide a precis of our initial efforts to test and evaluate the outputs of a synthetic catalogue of earthquake ruptures for New Zealand. The earthquake catalogue has been generated using a Rate-State earthquake Simulator "RSQSim". The simulator uses a physics-based model of rupture nucleation and propagation to forecast long term earthquake catalogues, for example, hundreds of thousands of years. The long-term earthquake catalogue has been produced from the fault source model of the 2010 National Seismic Hazard Model (NSHM). Sub-catalogues of 180-year durations are withdrawn from the long term simulated catalogue, and these are compared to the 180-year historical record of earthquakes by way of magnitude-frequency distributions. The comparisons are limited to earthquakes recorded inside the same fault polygons used in the original simulations. Comparisons are also made to the 2010 NSHM fault source model (i.e., limited to purely fault-based earthquakes M>7.2 in the 2010 NSHM). Initial results show that the simulated earthquake rates agree well with the historical earthquake rates, but tend to underestimate the 2010 NSHM fault model rates.

Generating synthetic earthquake catalogs with RSQSim: impact on input parameters

Yi-Wun Mika Liao[1,2,3], Bill Fry[2], Andy Howell[1,2], Andy Nicol[1]

[1] School of Earth and Environment, University of Canterbury, Christchurch, New Zealand

[2] GNS Science, Lower Hutt, New Zealand

[3] Earthquake- Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, Taoyuan, Taiwan

The determination of the input parameters for hazard assessment, such as recurrence interval of earthquakes for a given magnitude, rupture initiation on the fault, and probability of multiple-segment rupture etc., is quite difficult, especially for large earthquakes (M>7.0). Physics-based earthquake simulators are one solution to assess uncertainties of hazard-related input parameters. Earthquake simulators such as RSQSim generate long-term synthetic earthquake catalogs, which may help reduce the uncertainties of the inputs of hazard assessment. In order to obtain realistic earthquake catalogs for hazard assessment with RSQSim, we input different fault and initial stress models for the Hikurangi-Kermadec-Tonga subduction zone. The results are compared with the observed earthquake catalog to verify the realisticness of the synthetic catalogs. The comparison between fault models with all three segments and only Hikurangi and Kermadec segments shows that the entire Hikurangi-Kermadec-Tonga subduction zone has potential to generate events with magnitude lager than 10 because of the long fault length (more than 3,000 km) and higher slip-rate at the Tonga segment. Since we have only little understanding of M10.0 events and the Tonga segment, we decide to keep only Hikurangi and Kermadec segments for further simulation. The comparison between different initial stress models shows that using variable values instead of a uniform value for initial stress on the fault plane can help generate more realistic synthetic earthquake catalogs. With the confidence given by the results, the heterogeneity of other stress parameters, such as initial friction coefficient and coefficient of rate and state dependence of friction (a and b), can be applied to the RSQSim inputs as the next steps to improve the realisticness of the synthetic earthquake catalogs.

Development of High-Resolution and High-Accuracy Shake-Map for Earthquakes in Taiwan by Implementing H/V Fourier Spectral Ratios

Shu-Hsien Chao[1], Che-Min Lin[2], Jyun-Yan Huang[1], Chun-Hsiang Kuo[3]

[1] National Center for Research on Earthquake Engineering, Taiwan

[2] National Center for Research on Earthquake Engineering, Taiwan

[3] National Central University, Taiwan

Shake-Map represents spatial distribution of the observed and predicted ground motion intensities (GMIs) of an earthquake. It provides essential and important information for emergency response after a damaged earthquake occurred. In this study, we propose a methodology for developing Shake-Map for earthquakes in Taiwan with high-resolution and high-accuracy from limited on-line strong motion instruments through using Taiwan ground motion prediction equation, spatial correlation model, average shear-wave velocity of 30-meters depth (Vs30) map with high resolution, and high density horizontal-to-vertical Fourier Spectral ratios from micro-tremors (MHVRs). We demonstrate the proposed methodology for several earthquakes by using the ground motion records of limited on-line strong motion instruments to develop Shake-Map, and evaluate the performance of the Shake-Map by using the ground motion records of all other off-line strong motion instruments. It is shown that the predicted GMIs can be derived more accurately for the locations which have no strong motion instrument by using the methodology proposed in this study.

Keywords: Shake-Map, Ground Motion Prediction Equation, Spatial Correlation, Spatial Interpolation and Extrapolation, Horizontal-to-Vertical Fourier Spectral Ratios

Theoretical shear wave radiation patter build in Fourier amplitude spectra and pseudo spectral acceleration ergodic ground-motion models in Taiwan

Jyun-Yan Huang[1], Chih-Hsuan Sung[2], Shu-Hsien Chao[1], Norman A. Abrahamson[2]

[1] National Center for Research on Earthquake Engineering, Taiwan

[2] Department of Civil and Environmental Engineering, University of California, Berkeley, USA

Development of non-ergodic ground motion model (GMM) would become the next step of the probability seismic hazard assessment in worldwide application owing to the need of site specific ground motion response in many cases. However, the accuracy of the nonergodic term would depend on how comprehensively of each physical term been built firstly in ergodic GMM. It means if there were more detail behaviors controlled from ergodic GMM that non-ergodic terms could capture more accurate scaling in seismogenic source regions, grid-path or local site response. Hence, in this study, we focused on source radiation pattern that were mostly lack in previous GMM development owing to lack of densely seismic records from relatively short history of instrumentory measurements compared to longer scale in nature to cover whole range of possibilities of the effect. We calculated the source radiation pattern from pseudo bending ray tracing technique (Um and Thurber, 1987; Koketsu and Sekine, 1998) followed the point-source theoretical double-couple behavior in an arbitrary orientation homogenous media (Aki and Richarts, 1980; 2002) for each record in ground motion database of the National Center for Research on Earthquake Engineering (NCREE) Taiwan Senior Seismic Hazard Analysis Committee (SSHAC) level 3 probabilistic seismic-hazard analyses (PSHA) project. The frequency-dependent trends were found in small magnitude events (M <6) which was corresponding to the theoretical point-source suggestion, and were built in both ergodic GMM of pseudo spectrum acceleration (PSA) and Fourier amplitude spectrum (FAS). Meanwhile, that we provide a phase-difference model for radius to transverse component and further connect to Boore's ω^2 spectrum point-source simulations in discussion section to solve the inconsistent of orientation problem in an orientationless theoretical coefficient, an indeterminate directional RotD50 used for PSA and an orientation-independent effective amplitude spectrum. Finally, although the reduction of uncertainty for ergodic GMMs was not significant, the importance of this study was to prevent fause-captured of the non-ergodic path term from record-to-record residual.

Toward Seismic Hazard Assessment Using Physics-based Ground Motion Simulation in Taiwan

Ming-Che Hsieh[1], Kuo-Fong Ma[1,2]

[1]Earthquake-Disaster & Risk Evaluation and Management Center, National Central University, Zhongli, Taiwan

[2]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

Damages to buildings and infrastructures by an earthquake depend on the entire time history of the ground motion, which is affected by several factors, including source-rupture process, seismic-wave velocity structure, topographic relief, and local site condition. To quantitatively assess these effects on ground motion, physics-based ground motion simulation is a powerful tool that enables rigorous modeling of each effect and coupling between effects. This presentation will show how we utilize motion simulations with accounting for physical factors to deterministic seismic hazard assessment. Both 3-D finite-difference and stochastic methods are selected to model long- and short-period synthetics, and ground motion parameters, e.g., PGA, PGV, PGD, SA0.3, and SA1.0, are retrieved from these synthetics. In our practices, crustal events in northern and southern Taiwan, and subduction zone events to the east of Taiwan have been addressed to estimate ground motions in metropolitan areas. Therefore, these simulated ground motion datasets are imported to loss estimation for earthquake drills annually. In addition, we also adopted ground motion simulation techniques to adjust functional forms of ground motion prediction equations (GMPE). Our preliminary results show that ground motion simulation can be treated as a basis to reduce the aleatory variability of GMPE.

Keywords: ground motion simulation, seismic hazard assessment, finite-difference method, stochastic method

Incorporation of 3-D Simulation Results Into Non-ergodic Ground-Motion Models: A Case of Megathrust Earthquakes on Cascadia Subduction Zone

Chih-Hsuan Sung[1], Norman Abrahamson[1]

[1] University of California, Berkeley, USA

Non-ergodic effects on the ground motions in Cascadia can be seen in the suite of numerical simulations of ground motions from megathrust earthquakes on the Cascadia subduction zone through a 3-D crustal structure developed by the M9 project (Frankel et al., 2018). These observations led to the move from ergodic to non-ergodic ground-motion models (GMMs). The Abrahamson and Gulerce (2020) GMM (AG20) is modified to include the non-ergodic effects from the 3-D simulations. First, the scaling of the basin effects as a function of the depth to a shear-wave velocity of 2.5 km/s (Z2.5) in the AG20 model is modified to be consistent with the Z2.5 scaling from the 3-D simulations. Second, the spatial distribution of the non-ergodic site terms is estimated using the varying coefficient model for the region covered by the 3-D velocity model. With the non-ergodic site terms, the aleatory variability for the 3-D simulations reduced by 15-25% compared to an ergodic standard deviation for Cascadia. In addition to an average single-station sigma, a spatially varying single-station sigma model is developed which shows the highest variability for sites near the basin edges. The epistemic uncertainty in the non-ergodic site terms for a single 3-D velocity model is small, but there will be uncertainty due to alternative 3-D models. Without simulation results for different 3-D velocity models, we set the epistemic uncertainty to be one half of the between-site standard deviation from the simulations. The resulting non-ergodic GMM can be used in seismic hazard analyses that include site-specific basin effects for the median and aleatory variability for interface events in the Seattle region.