A Comprehensive Probabilistic Earthquake and Tsunami Risk Model for Japan

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Abstract

The importance of catastrophe risk modeling has significantly increased in Japan due to a series of devastating events, the rapid evolution of exposure and the diverse usage of risk models in the insurance and reinsurance industries over recent decades. In order to quantify the dynamically changing seismic risk, we developed a probabilistic seismic risk model of Japan including a probabilistic tsunami component using a simulation-based, high-definition (HD) modeling framework. The model introduces new science, innovations and important lessons learned from recent major earthquakes in Japan, including the 2011 Tohoku and 2016 Kumamoto earthquakes.

We present the outline of the HD modeling framework, component development with underlying information used, loss calibration and its results focusing on model validation. This paper consists of five major sections.

- First, the advantages of the simulation-based HD framework are discussed: temporal and spatial sampling, stochastic exposure disaggregation, four parameter secondary uncertainty distribution, ground-up risk-level loss simulation, and enhanced financial loss module to accommodate Japan specific complex policy structures.
- Second, the main elements of the source model feature the latest research from the Japanese Headquarters for Earthquake Research Promotion (HERP) combined with our own Japan megathrust recurrence models, in particular a Bayesian view on time-dependent rates for Nankai Trough events.
- Third, a new study on the application of locally derived ground motion, site amplification and sedimentary basin models was conducted. High-resolution geographical data layers were created for seismic hazard and secondary perils. The model utilizes these components that vary by tectonic settings (e.g., subduction interface versus active crustal), hypocentral depth (e.g., shallow versus deep), moment magnitude, fault geometry parameters, and site conditions based on the calibration with extensive number of strong ground motions recorded in Japan. Comparisons of modeled vs observed JMA intensity footprints for key events are included. For near surface site amplification and liquefaction, 90m base resolution data layers, such as time-averaged shear wave velocity to 30m depth (V_{S30}), Multi-resolution Valley Bottom Flatness (MrVBF), and groundwater depth are implemented for a more accurate representation of perils with a high hazard gradient in areas of concentrated exposure.
- Fourth, a suite of vulnerability functions was developed by comparing modeled numbers of damaged buildings, economic and insured losses, and regional distributions of damage based on field observations (e.g., Tohoku and Kumamoto earthquakes). Incremental dynamic analyses have been performed as well using multiple representative building models designed by local engineers with more than 13k observed ground motions between 1996 and 2017.
- Lastly, we demonstrate the fitness of the model with comparisons to recent events including comparisons for more than 15 historical major events, key government scenarios such as Toshin Nanbu, Nankai-Tonankai events, ground shaking versus tsunami loss contribution ratios and the General Insurance Rating Organization of Japan (GIROJ) industry losses. Exceedance probability loss metrics and loss costs by region and by lines of business are examined.

Details of the tsunami model component, spatial loss correlation associated with source characteristics and nonlinear site/basin amplification modeling are presented in separate papers. [1,2]

Keywords: Probabilistic Risk Model; Loss Estimation; Japan Earthquake Risk; Tsunami Risk; Insurance

1. Introduction

The Japanese Islands lie in one of the world's most seismically active areas. They span the boundary between the Eurasian Plate and the Okhotsk Plate, and are bounded to the east by the Pacific Plate and to the south by the Philippine Sea Plate. Subduction of the Pacific and Philippine Sea plates beneath the Eurasian Plate accounts for most earthquakes in Japan, as well as for the extensive volcanism that created the Japan Islands.

RMS aims to provide a comprehensive view of portfolio risk for insurance markets in Japan. The earthquake model provides a comprehensive solution to capture earthquake risk across Japan from earthquake ground shaking (accounting for liquefaction and landsliding), tsunami, and fire following earthquake (FFEQ).

The importance of catastrophe risk modeling has significantly increased in Japan due to a series of devastating events, the rapid evolution of exposure and the diverse usage of risk models in the insurance and reinsurance industries over recent decades. In order to quantify the dynamically changing seismic risk, we developed a probabilistic seismic risk model of Japan including a probabilistic tsunami model using a simulation-based, high-definition (HD) modeling framework. The model introduces new science, innovations and important lessons learned from recent major earthquakes in Japan, including the 2011 Tohoku and 2016 Kumamoto earthquakes.

2. Simulation-Based HD Framework

The HD modeling framework delivers ground-up simulation of risk losses by coverage and by sub-peril based on observed damage distributions. This underlying paradigm of the HD-simulation framework thus calculates realistic loss distributions at the highest level necessary to generate accurate losses. This approach provides a significant modeling advantage, in particular for modeling tsunami, liquefaction and landslide risk, as these sub-perils require detailed geographical information to generate a realistic loss result. RMS HD framework include following key components:

- Temporal simulation of hazard events—HD temporal simulation involves defining possible event occurrences on a timeline, or period. Each period is a multi-year realization of event occurrences over a specific time period. The outcome of temporal simulation is the weighted period event table (WPET), which contains the full set of simulated periods. Temporal simulation allows users to explore tens to hundreds of thousands of realizations within specified time windows and provide flexibility in the choice and application of occurrence models. Refer to more details in Fitzenz et al., 2020 [2].
- New severity distribution uncertainty approaches—Sampling event losses from the damage distribution provides modelers with the flexibility to choose the most realistic distribution to describe the damage ratio of event severities for a given peril. HD models use four-parameter, secondary-uncertainty distributions, enabling the model to explicitly capture the probability of zero or total damage from a given level of hazard.
- Greater financial modeling capability—With the HD financial module, users can express all possible terms and conditions in an insurance or reinsurance contract and use the HD financial model to analyze losses from any desired contract specification. Japan-specific, complex-policy structures such and step policy and franchise deductible at any risk level are available
- Auto disaggregation functionality—When model users only have Prefecture or CRESTA exposure, the disaggregation engine automatically distributes the exposure down to the chōme (in regions exposed to tsunami, liquefaction risk or in the central business districts) to enable the model to continue to run at the required resolution by aggregating losses from disaggregated locations.
- Sub-peril aggregation (shake, FFEQ and tsunami)—In the HD-simulation framework, the model samples damage ratio for each sub-peril for each building and then the sub-peril aggregation module defines the rules on how the model adjusts the losses for each sub-peril to reflect how the claims may be distributed across the sub-peril coverages.

3. Source Modeling

The RMS earthquake rupture forecast model is based on the database of earthquake sources and underlying data of the 2017 National Map of Earthquake Prediction of the Earthquake Research Committee (ERC) of the Headquarters for Earthquake Research Promotion (HERP) under the Japanese ministry of Education, Culture, Sport, Science, and Technology (ERC, 2017). These maps and related products (including tables and map objects from the Japan Seismic Hazard Information Station (JSHIS) website) are referred to as HERP 2017 in the remainder of this document. In addition, RMS reviewed each component and complemented or revised them where more information could be brought to bear. In that context, the 2013 report by ERC [3] on “Long-term evaluation of seismicity along Nankai Trough,” as well as the ERC report on seismicity in the Sagami Trough region and Satake (2015) [4] were very useful in pointing out that there are very different estimates for the 30-year conditional probabilities for large events, for example on the Nankai trough. The time-predictable model with uncertainties (ERC, 2016) [5] yields 60%–70%. The long-term evaluation report on the Nankai interface (ERC, 2013) also reports a 30-year BPT conditional cumulative density functions (CDFs) of 6%–30% and a Poisson CDF of 20%. The existence of these very different perspectives motivated us to revisit this question.

3.1 HERP 2017 Components

HERP 2017 includes several elements. Crustal faults are characterized as planes informed by geological mapping. Their earthquake occurrence models are informed by paleoseismology and historical and instrumental earthquake records and chosen as coming from time-dependent, Brownian-Passage-Time (BPT) distribution with very small aperiodicities (quasi-periodic models). They are computed as 30-year probabilities. Small to medium crustal, interface and intraslab sources have time-independent rates that are defined through catalog analysis, and locations that honor the geodynamics of the region. Their geometry goes from line sources for the smallest events (a.k.a., background events) to rectangular sources of increasing size as the magnitude increases (a.k.a., medium-size events). The line sources use Matsuda (1975) for magnitude-length relationship, which created notably shorter events than most other scaling laws for the same magnitudes. Note also that the medium size events that are on the Japan trench are chosen as tiles that cover the whole Japan trench and do not cover only the location of past M8 events (e.g., Miyagi-oki and northern Sanriku-oki). This is a departure from previous (i.e., pre-Tohoku) HERP models. Finally, megathrust events with magnitudes up to around M9 are considered on the Kuril subduction interface, the Japan trench interface, in the Kanto region (Sagami Trough), and on the Nankai interface (see Fig. 1). The geometry of the sources is given by complex point clouds and their segmentation reflects past seismicity. Their 30-year recurrence probability relies on date of most recent event, average recurrence between (3 to 5) most recent events by segment, and a small aperiodicity, except for Sagami and Nankai. For Sagami, the mean recurrence and aperiodicity come from maximum likelihood using the last 3 events in the Kanto region and assuming the BPT model. For Nankai, a time-predictable model with some uncertainty is used and also takes the form of a BPT distribution with a small aperiodicity.

3.2 RMS Enhancements.

A) RMS used the length of crustal fault sources in HERP 2017 to test the scaling relationship and found that sampling the Takemura (1998) [6] for events smaller than 6.5 and the global Wells and Coppersmith relationship for events larger than 6.5 allowed best consistency.

B) JSHIS models crustal faults as planes, with one point defining beginning and end of the fault. RMS updated this with the complex traces from internal RMS development, but maintained the geometry (dip and depth) and reoccurrence parameters defined in the HERP 2017 model.

C) RMS reviewed the shape of the likelihood contours for the Sagami megathrust events, as well as the rich data sets and models presented in the Sagami report. Given the very broad interevent time distribution obtained by scientists sampling from the ages of the uplift terraces, the complexity of the scenarios that are folded under the “Sagami trough” source, and the very flat and broad likelihood for the BPT parameters obtained using only

3 events (the 1923 Kanto event, the 1703 Genroku earthquake, and an event in 1293), RMS decided to use the whole posterior probability to build the recurrence model, not just the maximum likelihood parameters.

D) Finally, many emergency and risk management applications require quantifying a probability for large events conditioned on the time since the last event. When the seismic source is complex and has either a geometry or a faulting behavior that does not directly obey the hypotheses of simple renewal models, it is important to design strategies so that useful information can still be transferred to the stakeholders. Japan, and more precisely, the Nankai Trough, presents a case in which segments of a given source can either rupture on their own but in clusters (here, in pairs) or rupture all together in one very large event. Although the region has a spatial distribution of small to moderate interface events that does not seem to obey any segmentation, the megathrust events have happened quasi-periodically since 684 and have either ruptured at least the two central segments at once (Nankai Y and Tonankai X) or at least the two central segments in two earthquakes a few hours to a few years apart. A renewal model analysis of the Nankai segment or the Tonankai segment independently would only provide a recurrence model for events “at least as large as” for each segment, and the information on the clustering would be lost.

HERP 2017 decided to compute the recurrence of large events and then to apportion this rate to a number of possible scenarios according to their relative likelihood of occurrence knowing the long history of past events in that region. The Nankai report shows that different methods lead to very different estimates for the budget for large megathrust events. The method retained in HERP 2017 uses the time-predictable model value for the time to the next event, plugged into a BPT distribution with a small aperiodicity.Given that megathrust events on the Nankai subduction interface cause losses over a wide area and in particular in industrial and highly populated regions (in particular in the eastern sections), the recurrence of these events contributes significantly to the risk landscape of Japan. A small aperiodicity leads to very high hazard rates (or small effective recurrence) when the time since the most recent event becomes close to the mean recurrence time. However, the smaller the effective recurrence, the larger the required reserves for solvency purposes. How the uncertainty on recurrence is handled is therefore very important.

RMS developed an original method to better constrain this budget. It uses the history of past events to build the likelihood of the BPT model parameters (including the open interval). For this purpose, each pair of adjacent events is considered as one renewal model event.

Then convergence rate and slip per event information inferred for the Nankai Trough area in numerical simulations of megathrust events are combined to build an empirical prior for mean recurrence time [7]. The weighted average of all BPT distributions (with weights equal to posterior probability of the parameters) is then used together with the date of last episode (1944) to compute the current hazard rate. Similar to HERP 2017, this rate is then apportioned to the various scenarios according to their relative likelihood.

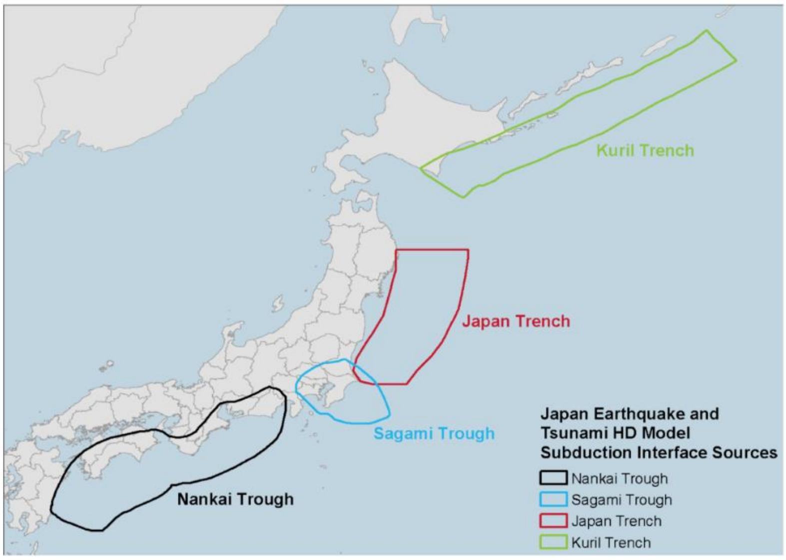


Fig.1 – Outline of megathrust sources

The RMS model follows a simulation methodology. To create time series, the last step is to constrain the time between events in a pair. Given the few documented times between events in a pair, we chose a lognormal distribution such that half of the pairs are complete within 1 year, 75% within 2 years and 90% within 3 years.

E) The suite of stochastic events was enhanced with a magnitude uncertainty around the nominal magnitude for each HERP 2017 scenario. Note that for the tsunami part of the model, each scenario-magnitude was assessed for how likely it was to give rise to a tsunami.

4. Ground Motion Modeling

The seismic hazard module in our Japan Earthquake HD Model includes two additional elements: ground motion characterization and geotechnical soil data. Accurate ground motion characterization is very important in seismic hazard assessments. Strong ground motions caused by earthquakes can be measured by different ground motion intensity measures, *GMIMs*, such as peak ground acceleration (PGA), spectral acceleration (SA) and Japan Meteorological Agency intensity (JMA). Ground motion prediction equations (GMPEs) predict the mean ground shaking level at a site as a function of various predictor variables, which include source, path (i.e. site-to-source distance) and site effects along with the ground motion uncertainty. Additionally, the geotechnical soil data, i.e. time-averaged shear wave velocity to 30m depth (V_{S30}), is an important input for site amplification models that modify the ground shaking by incorporating the local site conditions.

JSHIS and HERP use a simple GMPE logic tree that is based on Si and Midorikawa (1999) whose prototype is Morikawa and Fujiwara (2013) model. Since Japan has one of the most abundant observed ground motion recordings in the world, RMS collected data from Kik-Net and K-Net, performed detailed data analysis and validation with key events to determine the candidate GMPEs suitable for Japan. Observation data flatfile from Dawood et al. (2016) [8] is included to augment the data. Accordingly, the Japan Earthquake HD Model implements a logic tree using tectonic regime dependent, locally derived Japanese GMPEs to capture Japanese ground motion characteristics properly, and epistemic uncertainty. The model calculates the ground shaking, at a location, as a weighted average from the suite of these GMPEs which are applicable to an event within a given tectonic regime (Fig. 2). The resulting *GMIM* represents the ground shaking under the standardized rock conditions (i.e. V_{S30}=760 m/s). The model then alters this *GMIM* using the surficial (default sediment depth) and/or sub-surficial (within sedimentary basin boundaries) amplification models that account for geologic and site conditions based on the location of the site (Fig. 3, see details in Kwak and Seyhan, 20xx, in press) [9]. Regarding the large ground motion uncertainty, the model implements alternative GMPE branches to help visualize the variability in ground motion uncertainty associated with the logic tree GMPEs. These GMPEs also vary regionally. This functionality in the Japan Earthquake HD Model enables users to 1) stress test the

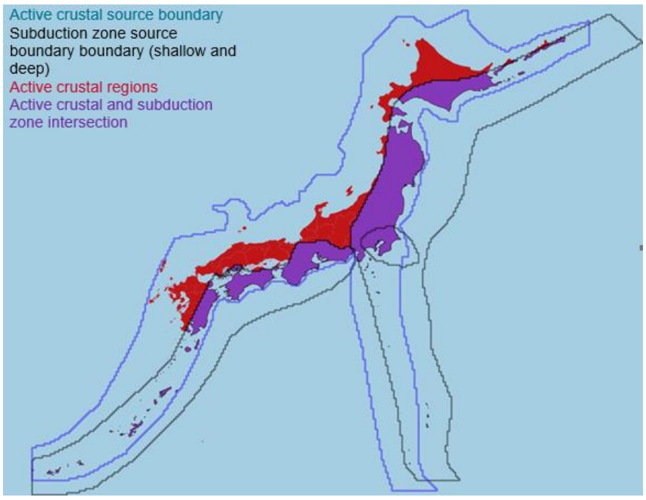


Fig. 2 – Tectonic regime specific GMPE regions in Japan

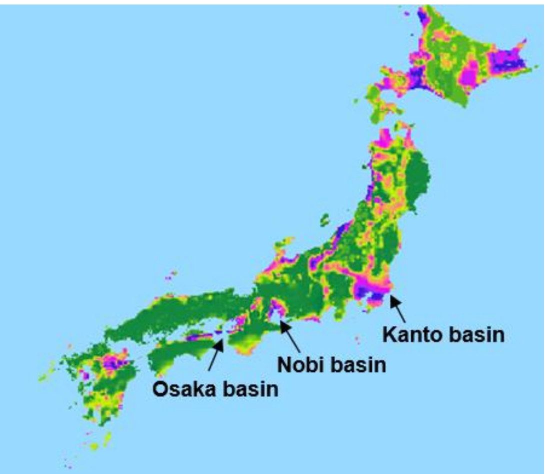


Fig. 3 – RMS site period map for entire Japan (green to purple color indicates the transition from short to long periods)

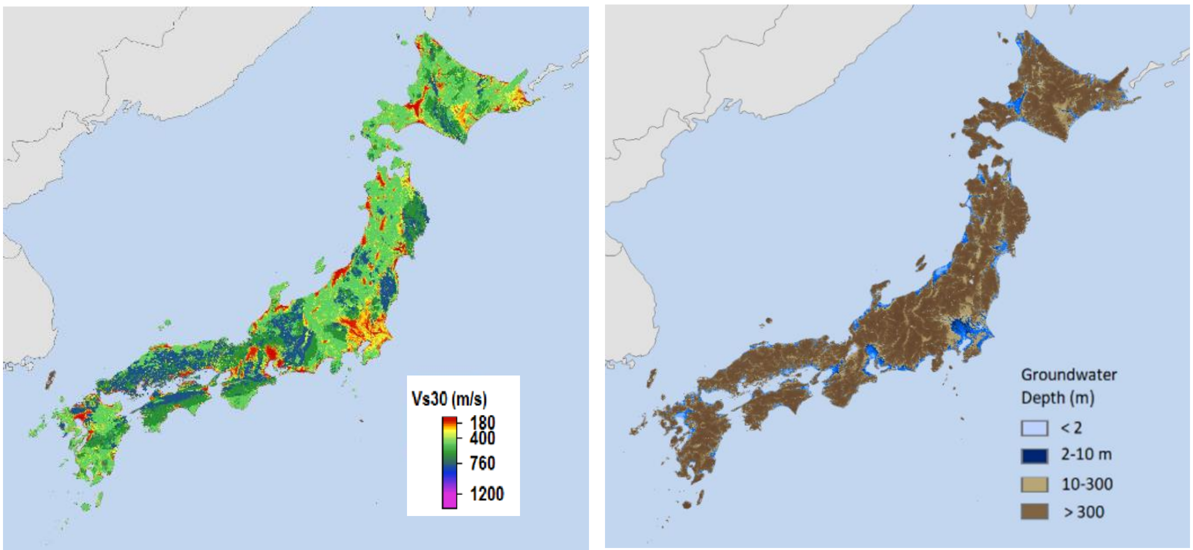
impact of modeled lower and upper bounds of the ground motions and 2) obtain reasonable range of insured losses around the RMS reference view of risk.

5. Geotechnical Modeling

Geotechnical hazards evaluated in earthquake loss models include modeling of the site parameters to predict ground motion amplification, liquefaction, and landslide as well as the building response to these co-seismic effects.

While the site response has been correlated to several factors this study proposes a new geostatistical methodology for mapping one of these parameters Vs30, the time-averaged shear wave velocity of the upper 30 meters. Estimating Vs30 in Japan is improved utilizing a new geostatistical spatial prediction model. The new Vs30 map was focused on improving spatial prediction of Vs30 using a new trend, the spatial variability in the median value. The new map uses a combination of surface geology and multiple resolution of valley bottom flatness, MrVBF, for unconsolidated geology units and surface geology for lithified units. The map of Vs30 for Japan is shown in Fig. 4a.

An accurate spatial representation of the near surface or depth to the first occurrence of groundwater improves the prediction performance of liquefaction loss models. If groundwater is below a susceptible layer, that layer is unlikely to liquefy. Monitored groundwater depth, in general, becomes sparse and discontinuous over space, which leads to inaccurate geostatistical estimation. Fortunately, auxiliary digital elevation model output (DEM) correlated with the ground water elevation becomes available over much of the Earth’s surface. At the same spatial grids another auxiliary distance to water body (DWB) can be obtainable using GIS techniques, namely a Euclidean distance calculation. Through an external drift model within a geostatistical estimation framework and local Kriging where monitoring stations are dense, we predict a groundwater depth for the specific application in prediction liquefaction damage as show in Fig. 4b.



Figs. 4a and 4b – Vs30 and groundwater depth map of Japan

5. Vulnerability Development

The Japan Earthquake HD Model vulnerability functions are spectral response-based functions, which RMS developed using the latest research studies in performance-based earthquake engineering. RMS calibrated and validated the vulnerability functions using billions of dollars of claims data from the 2011 Tohoku and 2016 Kumamoto earthquakes in addition to damage statistics from older events such as 1995 Kobe and 2004 Niigata Chuetsu earthquakes. This section introduces overall framework and key vulnerability components.

5.1 Inventory Database Based on Japan Specific Building Classifications

The risk classification scheme and vulnerability functions work in combination with a Japanese building inventory database, which is explicitly defined within the Japan earthquake vulnerability module. In cases where a building's occupancy, construction class, age, or height is not specified, the vulnerability module uses a building inventory database to develop a composite vulnerability function for the location of interest. RMS classification schemes include Japan specific fire insurance scheme. The building inventory is defined at city/ward resolution and split into seven different regions primarily based on building height. Fig. 5 shows inventory region assumptions in city/ward resolution in the vicinity Tokyo and Fig. 6 represents the inventory distributions by year built and height in high urban area (H7 region). For the inventory development, RMS created and used a building database (including more than 95 percent of building footprints with occupancies in Japan) and Japanese Construction Year Books to classify city/wards into the seven different inventory subdivisions and assign the distributions for construction, height, and year built by occupancy type. We also used the 2009 Housing Survey and the "2005–2010 Fixed Assets Summary Report," to incorporate more recent information and more specialized risks.

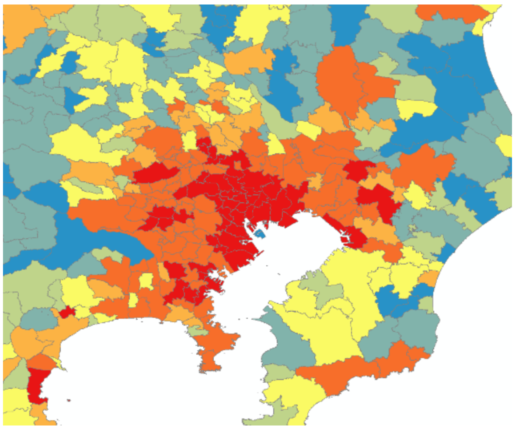


Fig. 5 – Japan earthquake building inventory assumptions in the Tokyo Metropolitan region H7 (High Urban) - H1 (Rural)

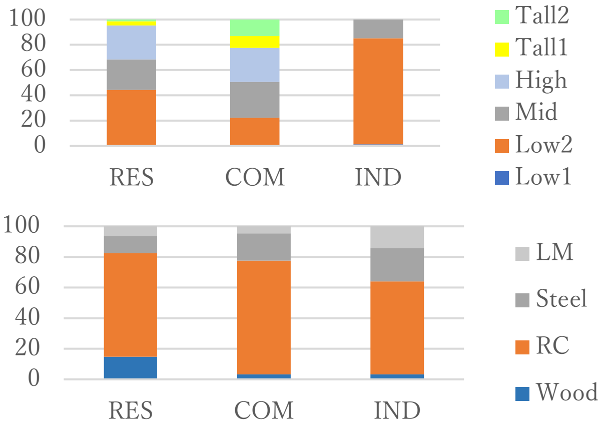
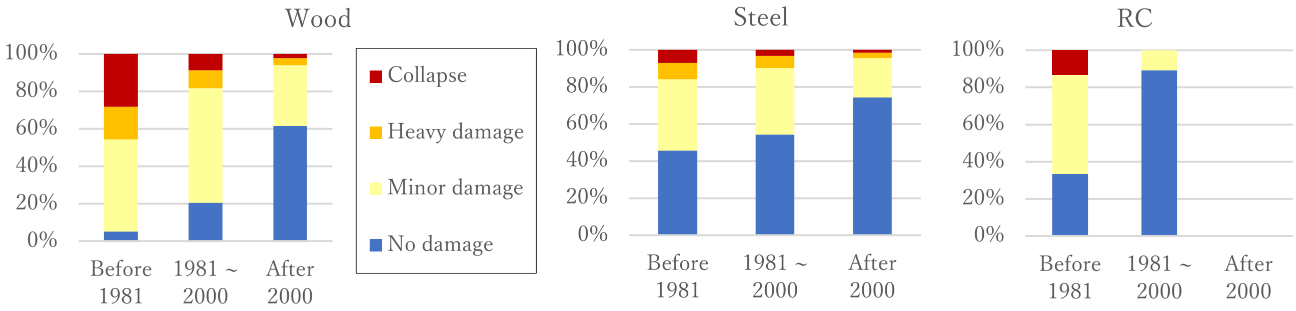


Fig. 6 – Year built and construction assumption in H7 (High Urban)

5.2 Empirical Approach Using Damage Statistics

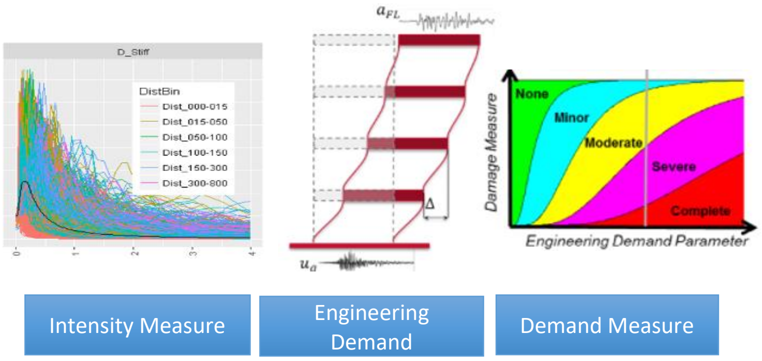
Vulnerability functions are affected by socioeconomic and cultural factors as well the fragility of the building. Accordingly, vulnerability function calibration using damage statistics and claims is as important as the analytical approach which will be discussed in the next section. Japan has a great track record collecting damage statistics since Edo Era and RMS reconstructed nationwide losses for major historical events since 1891 as introduced in Section 6. Vulnerability relativities by construction, year-built and height were primarily derived based on events after the 1995 Kobe earthquake, which include recent the 2011 Tohoku and the 2016 Kumamoto earthquakes. Figs. 7 shows examples of damage statistics from the Kumamoto earthquake [10]



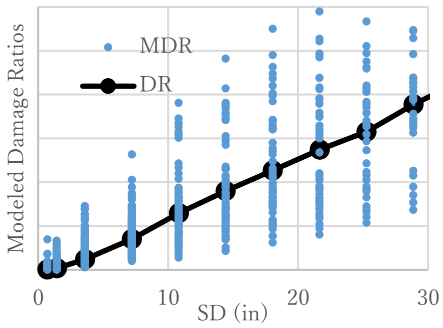
Figs. 7 – Damage statistics from the Kumamoto earthquakes, Mashiki Town, Kumamoto Japan [4] used for year-built relativity. 2,340 buildings in Mashiki Town, Kumamoto Prefecture including undamaged buildings were studied and figures clearly show unique trends in year-built by construction. Damage states were translated into damage ratios using associated repair costs to drive relativities among different constructions.

5.3 Analytical Approach Using Structural Models

While damage statistics and claims data are useful to validate the core of the vulnerability model, there are many combinations of construction class, height, and structural characteristics that need to be differentiated. To fill in the gaps in the observation data, RMS creates analytical models to assess structural performance. Fig. 8 provides a schematic of the provides a schematic of the simulation framework for developing these "base" vulnerability curves. RMS analyzed incremental, dynamic non-linear time histories (IDA [11]) for seven representative reinforced concrete (RC) and steel buildings with four different heights (3F, 6F, 12 and 17F) provided by Japanese engineers. K-NET/KIK-Net strong motion data with peak ground acceleration (PGA) greater than 0.1g from 1996 to 2017 were used across a range of distances, magnitude, source type and site conditions (13,600 ground motions in total). We then convert the analytical results, inter-story drift, floor acceleration, and ductility ratios to a building damage ratio using the component level (drift and acceleration sensitive separately) fragility related information provided by local experts, experimental studies and observed damage statistics primarily from 1995 Kobe earthquake on the performance evaluation of each building component. Fig.9 includes incremental dynamic analysis results for RC 12F buildings.



Figs.8 – Schematic of the simulation framework for developing seismic vulnerability curves



Figs. 9 – Incremental Dynamic Analysis Results for RC 12F Building (Post 1981 Code)

6. Probabilistic Tsunami Model

The devastating tsunami events including the Japan 2011 tsunami and Indian Ocean 2004 tsunami had major impacts on the coastal communities. Tsunami risk had been previously assessed by the limited number of scenarios due to the lack of data and the complexity of tsunami hazard and vulnerability modeling. Great progress in collecting data, scientific improvements of tsunami assessment and modeling, and the huge technological improvements of parallel computation in recent years now enable us to model tsunami inundation hazard at very fine resolutions.

The RMS tsunami model combines the Probabilistic Tsunami Hazard Assessment (PTHA, Farahani et al., 2020) [1] with detailed vulnerability, exposure and financial models to identify the loss estimation and tsunami risk. RMS tsunami model includes the following components:

1) Tsunamigenic Seismic Source Identification: The geometry and magnitudes of the tsunami sources are derived from the set of sources (Fig. 10) that are provided by HERP through the Japan Seismic Hazard Information Stations (http://www.j-shis.bosai.go.jp/en/). For each tsunamigenic source, a set of stochastic slip distributions has been modeled as input for deformation modeling.
2) Ocean/land Deformation Model: This component calculates the deformation caused by the tsunamigenic earthquakes both for the ocean and land. The deformations at the ocean generate the initial tsunami waves and the deformations at the land are used to adjust the land elevation after the earthquake.

3) <u>High-resolution Numerical Wave Model:</u> Nonlinear shallow water equations are numerically solved to simulate the wave propagation and coastal inundation. The wave model includes three layers of nested grids and the finest grids have a resolution of 50 m^2 and cover both east and west coastlines of Japan. Variable land friction coefficients are used to accurately model the inundation patterns inland.
4) <u>Tsunami Vulnerability model:</u> Tsunami fragility curves are developed using the comprehensive data of Japan 2011 event. In the vulnerability model both tsunami height and tsunami velocities have been considered. [12]
5) <u>Tsunami Risk Assessment</u>: The probabilistic tsunami hazard is combined with the vulnerability, exposure, and financial models to deliver the tsunami risk assessment for eastern and western coastlines of Japan.

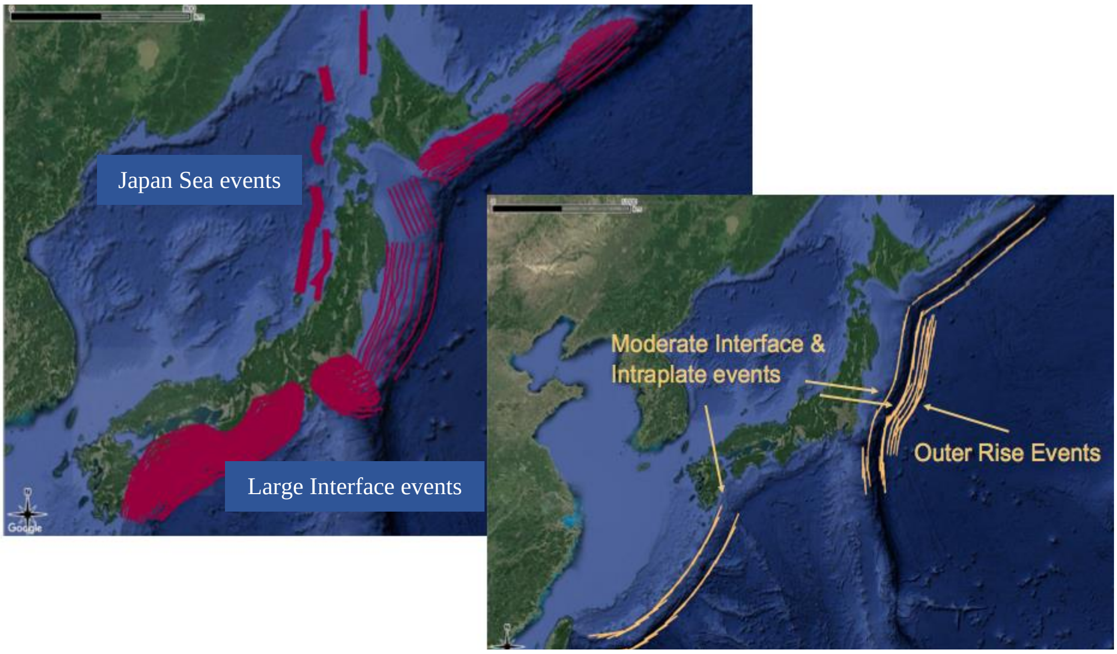


Fig. 10 – Location of tsunamogenic sources for the RMS Japan PTHA model. Lines displayed indicate depth contours of the different sources

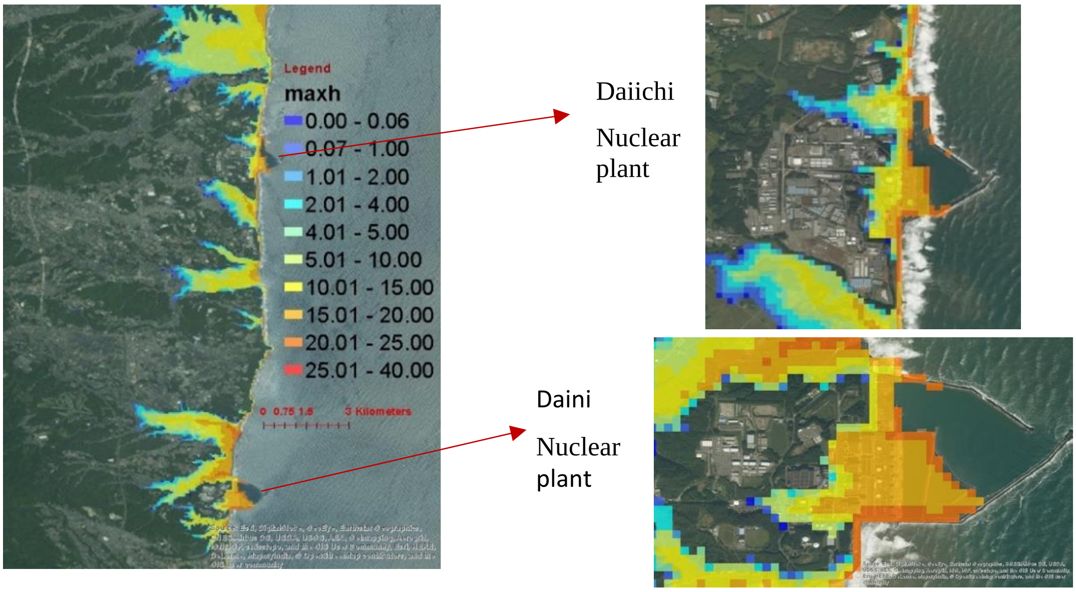


Fig. 11 – Inundation depths and extent at Fukushima region corresponding to one of Tohoku-like stochastic events.

The RMS probabilistic tsunami model includes roughly 750 stochastic footprints. The inundation maps of this stochastic set illustrate a large variety of coastal inundation due to the height of the initial wave generated in the ocean, the initial wave direction or their angle of incidence along the coast, the coastal profile, and other coastal processes such as wave reflection and edge waves. Fig. 11 illustrates the inundation depth and extent in the Fukushima region corresponding to one Tohoku-like stochastic event and slip distribution. The histograms of maximum water depth at Fukushima Daiichi nuclear plant and Fukushima Daini nuclear plant illustrate and emphasize the necessity of a probabilistic high-resolution model to identify the complexity of the tsunami risk in Japan. Detailed tsunami hazard curves and return period maps of different regions along the Japan coastline are provided in a companion paper by Farahani et al. (2020). A detailed description of the probabilistic model is found in Woessner & Farahani (2020) [13].

7. Model Validation

To validate a model, RMS compares model components and output with comparable benchmarks, and evaluates the results of each test. Catastrophe models represent complex physical processes to extrapolate rationally beyond a limited historical record. Multiple, independently calibrated component models each characterize a unique aspect of the overall process. The resulting model extrapolates far beyond the historical record, which for Japan earthquake is several hundred years.

To ensure that these extrapolations are feasible and consistent with recent experience, RMS validates model components and losses against relevant, recent observations. However, loss benchmarks are not comprehensive or stationary in space and time. Losses experienced even 10 or 15 years ago would be very different if the same event occurred today, due to ongoing changes to the building stock, infrastructure, mitigation measures (such as building code updates), insurance penetration, policyholder behavior, and insurance policy conditions. In addition, the loss record is relatively short for validating catastrophe losses. Standalone comparisons with loss benchmarks therefore cannot conclusively validate loss results, particularly for extreme events or worst-case scenarios. As well as loss validation, RMS therefore validates each model component, using the relevant science and data for that component.

The RMS model contains 18 historical event reconstructions, including the major events in the Tohoku and Kumamoto earthquakes. Since most of the 18 historical events have limited observed ground motion data, RMS models them by reconstructing the event rupture, and estimating the hazard using ground motion prediction equations (GMPEs). The 18 historical events therefore provide a view of what the losses could be if the event happens again in the future. Earthquake historical events are not frequent enough to establish longer-term loss metrics. To provide additional metrics of reasonableness, RMS calculates the return period of the modeled historical events based on the stochastic exceedance probability losses for the RMS 2018 Japan Industry Exposure Database (IED).

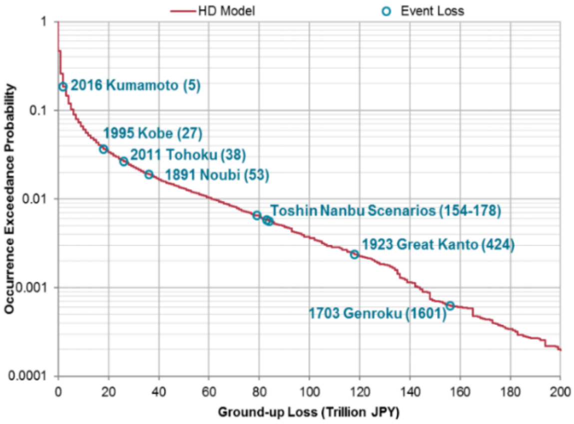


Fig. 12 – Exceedance probability curve: ground-up for all lines of business on the RMS economic exposure database with return periods for key historical events and scenarios provided in brackets

Fig. 12 shows return periods for key events on exceedance probability (EP) curves based on RMS economic exposure. As observed in the plot, return periods of well-known events in Kanto region such as the 1703 Genroku Earthquake, 1923 Great Kanto Earthquake, and Toshin-Nanbu scenarios are within expectation in the engineering community. The return periods of 2016 Kumamoto and 2011 Tohoku events are short, because the overall exposure within the footprints of these events is smaller than the nationwide total exposure.

Several sets of Japanese government loss estimates examine the potential impacts from key scenario events. As part of model validation, RMS compared both model losses and the distribution of losses to key government studies. Although, RMS and the government studies follow different approaches to estimate losses for given scenarios, the overall losses and event footprints are comparable. Fig. 13 compares the ground-up economic losses (residential, commercial and industrial combined) with the economic losses released for key government scenarios by the Cabinet Office.

As one of the final model validation steps, the team compared tsunami losses levels with the losses due to ground shaking on a per event basis. Fig. 14 provides this comparison for key events on the major subduction zones surrounding Japan. This plot shows that shows that Nankai events have high losses for tsunami and shake. Sagami events have high losses for shake but lower losses for tsunami, because most high exposure cities close to the Sagami trough are protected from high tsunami waves due to the coastline profiles.

8. Conclusions

The RMS Japan Earthquake and Tsunami HD Model incorporates key research advancements from the 2018 Japan Seismic Hazard Maps, as well as key lessons learned from the 2011 Tohoku Earthquake and 2016 Kumamoto Earthquake. Leveraging a substantial amount of detailed damage statistics and claims data from recent events, the RMS model assesses building performance due to ground shaking, tsunami inundation, fire following earthquake, liquefaction, and landslides. The inclusion of these five sources of potential property damage and business interruption losses provides a comprehensive solution for managing and differentiating the risk posed by earthquakes in Japan.

Fig. 15 shows maps of loss costs for commercial and industrial exposures across Japan. Loss costs are calculated by normalizing the annual average loss by the exposure value. The loss cost distribution is helpful for understanding the key drivers of risk and the risk relativities across regions and lines of business. Looking at both maps, it is clear the seismic risk in Japan is driven by the major subduction zones along the Pacific coast. The Tohoku region shows lower coastal loss cost because the model accounts for the fact that there was a very large event in this region in 2011 and that based on time-dependent recurrence modeling the rate of large events is now lower in this region compared the coastlines further to the south. The variations between commercial and industrial loss costs are driven by the differences in primary building characteristics (construction classes and building heights primarily) and how building with these characteristics are expected to perform in future earthquakes.

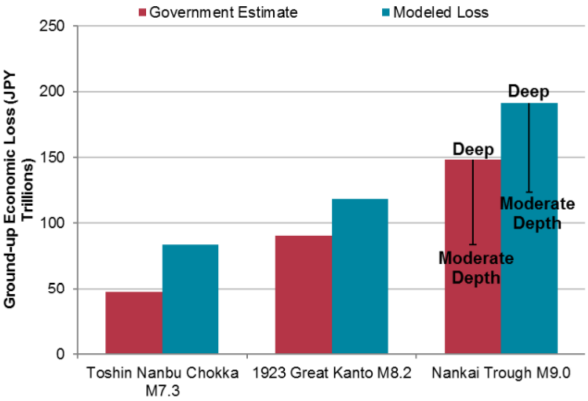


Fig. 13 – Ground-up economic losses combining residential, commercial and industrial for key government scenarios (Source: Cabinet Office)

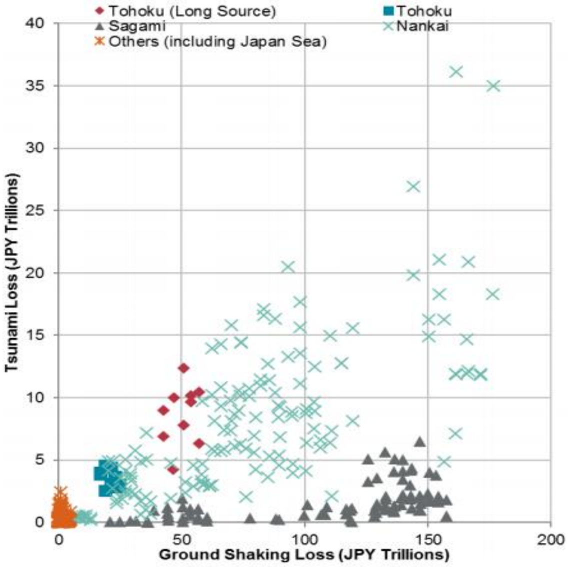


Fig. 14 – Tsunami loss versus shake loss for RMS tsunami set calculated in the expected mode

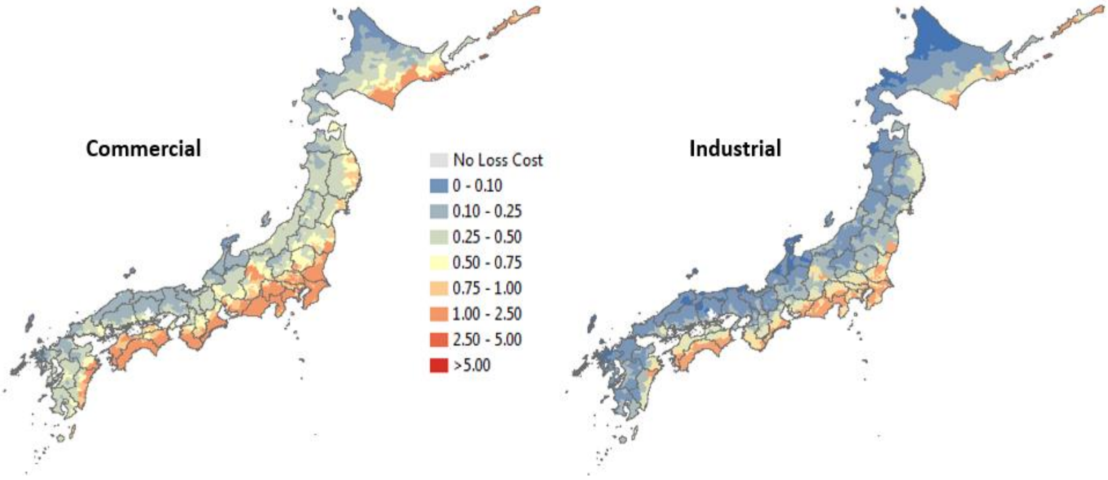


Fig. 15 – Loss cost maps for commercial and industrial exposures across Japan. Loss costs are calculated by normalizing the average annual loss by the total exposure value and are presented on a per 1k of value basis

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