LOSS MODELLING FRAMEWORK

Challenges in Catastrophe Modelling

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15 April 2020

Executive Summary

CAT models have come a very long way since their first days in the late 1980s, both in their maturity and peril coverage across the globe. Where do we go from here? This paper outlines five key challenges intended to spur model developers and evaluation specialists into action. The first and most important of these is the age-old chestnut of '*how can we validate a CAT model*'? This is still as difficult today as it was several decades ago, although we now have more historic loss events to work with. One thing we can do in this respect is develop a larger set of realistic disaster scenarios for region perils where there has not been a loss in modern times[1] that should, in principle at least, plot in the upper tail of the loss EP curve.

With that challenge under our belt, we turn our attention to filling gaps in the contingent peril model landscape, specifically aftershock, fire following and tsunami peril models. Fortunately, to do so does not require any new techniques or technologies to be developed, so these can be developed now.

We then briefly consider how to represent multiple alternative histories of loss causing events, such as a timeline of damaging aftershocks, or an event tree of multiple alternate tsunami or fire following earthquake outcomes, nested beneath a parent stochastic event. This 'alternate outcome' approach could equally be applied to atmospheric perils, including tropical cyclones, extra-tropical windstorms, wildfires and inland flooding. To implement an alternate outcome approach will require development of a loss modelling framework capable of large-scale concurrent parallel execution of alternate loss outcomes/ histories nested beneath a parent stochastic event, together with strategies to reduce the number of outcomes to a manageable number and to improve the model runtime.

The future appears bright in the world of CAT modelling. Innovation lies just around the corner. Our task in this is to point out where challenges and opportunities exist, regardless of current technological limitations. The ideas presented here could represent significant opportunities for model vendors. It will be interesting to see who goes out and makes them a reality.

[1] As is the case with most modelled region perils, globally.

Introduction

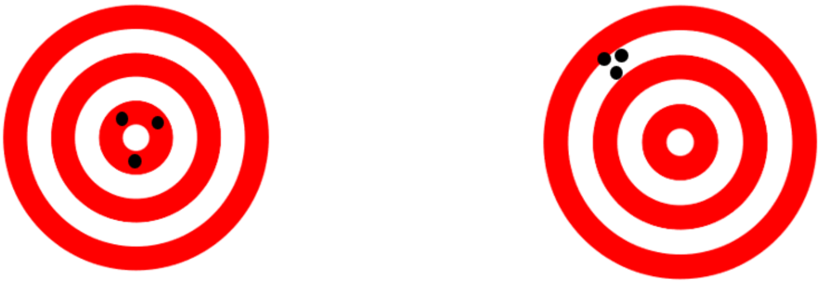
Catastrophe (CAT) models have added enormous amounts of value over the past three decades, by standardising the simulation of extreme CAT events and their risk metrics across the (re)insurance industry. They also routinely provide a sound basis for CAT risk accumulation, capital management and technical pricing across the industry; and can take a lot of credit for reducing the number of insurer insolvencies in the wake of large, unexpected CAT events. Models can and do face limitations, however, as we all do and as the modellers of the coronavirus pandemic are currently finding. For starters, the real world is a very complex place and resists efforts to reduce it to the confines of a model with relatively few, incompletely understood, often complexly interacting parameters. Nature also throws complete surprises at us, as happened in March 2011 with the unexpected magnitude of the subduction megathrust rupture of the Japan trench in the Tohoku earthquake, after which modellers played catch up. CAT modelling is not a finished art, there are still key areas needing further attention from model developers, such as the five challenges presented here. The purpose of this paper is to galvanise model vendors and model evaluation specialists into action to jointly meet these challenges.

1. Validating the Accuracy of CAT Models

The biggest challenge facing users of CAT models is simply how to tell whether it is accurate or not? Vendor CAT models can vary widely in the upper tail of the loss exceedance probability (EP) curve, at and beyond OEP 1:100.[2] The largest difference seen to date is a ten-fold difference between two models for the same region peril at OEP 1:250. Some users value such 'diversity' in view of risk. Others do not and instead prefer convergence of vendor model results, often on the basis of expectation of a certain size of industry loss associated with a particular return period. Clustered results can however be way off the mark (Figure 1b); the fact that they are clustered says little about modelling accuracy.

Figure 1. Schematic of the difference between accuracy and precision.

(a) High accuracy, low precision (b) High precision, low accuracy



Accuracy is assessed by comparing a measurement with an absolute benchmark. Unfortunately, CAT modelling has few absolute benchmarks. We do not know the probability of exceeding a loss threshold of a certain size in any given portfolio. It is the role of the model to estimate it. This makes it difficult to determine whether modelled loss results are credible, particularly in the upper tail of the loss EP curve (i.e. OEP 1:100 to 1:10,000) where events occur infrequently and there is a high degree of uncertainty around the event occurrence rate and the severity of the resulting losses. A common-sense approach often used to assess credibility of the upper tail is to benchmark the modelled return period of any extreme historic losses and realistic disaster scenario losses. If such losses plot either at a short or very long return periods then there may be reason for further investigation, as the model might be simulating losses of these sizes too frequently or

[2] Occurrence Exceedance Probability (OEP), the annualized probability of a single loss exceeding a specified size.

infrequently. Most often however there is usually little to distinguish whether the benchmarked return period is 'right' or 'wrong' in this respect. As a result, it can be difficult to prove or disprove the modelled loss EP curve in the upper tail.

We usually have greater confidence in the lower tail. This is because smaller, more frequent losses usually dominate both the lower tail of the EP curve and the expected loss. One way of benchmarking this is to define an insurance layer that attaches from-the-ground-up and exhausts at (for example) the AEP[3] 1:25 loss threshold. The modelled expected loss for this layer (either from the entire stochastic event set, or a subset that contributes heavily in this range) is then benchmarked against the indexed, annualised actual burning cost[4] of the portfolio for the past 25 years. The two should at least be broadly similar, if not then further investigation is required to explain the difference. Earthquake models in particular can be heavy in expected loss when compared with indexed actual loss experience.

Industry challenge:

- *To develop realistic disaster scenarios for region perils where no high-magnitude loss has occurred in the modern industrial era (as is the case for most region perils, worldwide), to allow the upper tail of the loss EP curve to be benchmarked. Although difficult to determine the absolute accuracy of the benchmarks in individual cases, comparison of groups of similar CAT models should reveal whether any models are relative outliers.*

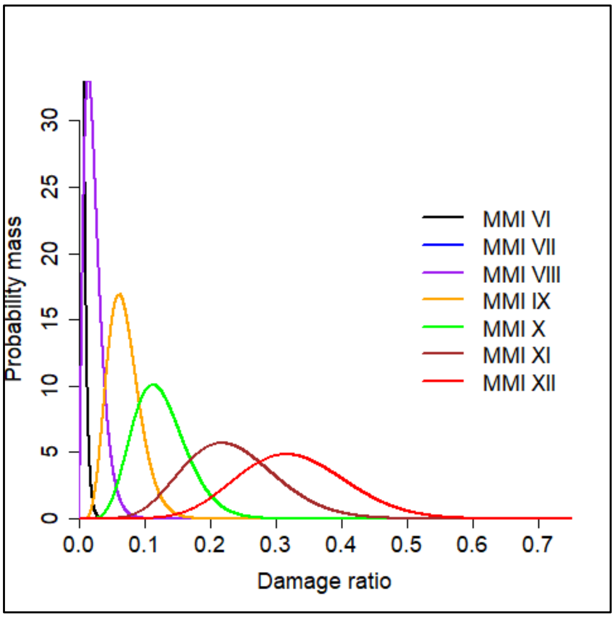
2. Modelling Individual Properties

CAT models used by the (re)insurance industry are designed to analyse CAT risk to portfolios of properties[5], rather than individual properties. They can also be used to calculate PML[6] to individual properties, as is routinely done in the U.S. real estate market on behalf of owners of individual residential and commercial buildings seeking to determine how much earthquake insurance cover to purchase. High-valued assets are also analysed as individual properties, including offshore platforms and onshore energy facilities. Where used in this way, the PML is likely to be understated where the peril is capable of causing total loss to the property (as is the case with earthquake, hurricane force winds and storm surge). We know this because the CAT modelled PML is typically much less than the total replacement value of the property. In contrast, PML figures of up to 100% of replacement value are often quoted in site risk surveys for some of these perils. Such high levels of damage are very unlikely to be seen from a CAT model designed for portfolio analysis. This is due to the aggregate damage functions used by the CAT model, which are designed for use with aggregates of properties rather than individual properties. For example, Figure 2 shows an aggregate damage function for earthquake ground shaking. At MMI VIII ('severe' shaking), the aggregate damage function does not exceed 10% damage, with a mean damage ratio (MDR) of only a few percent. At the highest possible level of shaking, MMI XII, the aggregate damage function does not exceed about 60%. In contrast, an individual property exposed to MMI XII shaking is likely to be irreparably damaged, most likely collapsed, given that this level of shaking intensity will

[3] Aggregate Exceedance probability (AEP), the annual aggregate probability of exceeding a loss of this size from all events in the year once aggregated together. AEP is to be used, rather than OEP, when comparing with the expected loss.
[4] Indexed actual claims experience averaged over the timeframe available. Large CAT losses are first removed, as these can heavily skew the comparison. Claims are also indexed to modern values, which can be very challenging given industry restructuring, changes in regulation, exposure distribution and changes to the insurance policy itself over time.
[5] 'Properties' here means buildings or facilities.
[6] Probable Maximum Loss, measured at the 90th percentile of the damage distribution for a single property (ATC, 2002).

significantly exceed any seismic design specification. It is impossible to represent this level of damage in the aggregate damage function.

Figure 2. ATC-13 damage distributions for class 4 (reinforced concrete shear wall with moment resisting frame, mid-rise, standard construction) under MMI VI ('Strong') to XII ('Extreme') shaking intensity. Reconstructed from damage functions published in ATC-13 (1985, 2002).



Creating an alternative set of damage functions suitable for use with individual properties is not a trivial task, requiring expertise from the fields of civil and structural engineering and seismology. Such damage functions cannot be derived from aggregate damage functions without completely changing the shape of the aggregate damage curves, which in turn would undermine the engineering basis from which the original aggregate damage functions were constructed. Only major model vendors are likely to have gone to the considerable effort of creating their own damage functions for individual properties; and even this may not have occurred in practice due to lack of necessity (because CAT models are designed for use with aggregate portfolios of properties, not individual properties). Minor model vendors are unlikely to possess the time, expertise and resources needed to create credible damage functions for classes of individual properties. They are instead much more likely to reuse existing public aggregate damage functions for this purpose, particularly ATC-13 and Hazus®. The Applied Technology Council (ATC) makes it clear in their subsequent commentary (ATC, 2002) that ATC-13 (1985) aggregate damage functions have been widely misapplied by structural engineers and that they should not be used for PML assessments of individual buildings. FEMA (2013, p29) takes a slightly more pragmatic stance, acknowledging that Hazus® damage functions are likely in practice to be applied to individual buildings, but advised that the results represent a group (i.e. an aggregate) of buildings, rather than a single building. Use of aggregate damage functions to analyse an individual building that is not part of a larger portfolio of similar properties will lead to underestimation of PML.

Industry challenges:

- *To develop publicly accessible catalogues of non-aggregate damage functions for a range of commonly encountered individual property (building or facility) types, for high-impact perils (earthquake ground shaking, hurricane wind, storm surge) capable of causing total loss. The USA is an obvious starting point for such a catalogue, liaising* *with key agencies such as the Applied Technology Council (ATC) and the National Institute of Building Sciences (NIBS).*

- *Once this is in place, to build a suite of CAT models suitable for use with both single properties and portfolios of properties. These models would dynamically select aggregate or individual building damage functions according to the number of buildings defined for the portfolio.*

3. Modelling Aftershocks

Aftershocks are earthquake events whose occurrence is entirely dependent on the occurrence of the mainshock, without which they would not occur. Thousands of aftershocks can occur in the weeks and months following a large mainshock, although typically only a handful are large enough to be damaging. These larger aftershocks, scattered across a wide area, can have much greater collective probability of impacting human and property exposure than the mainshock alone, for crustal earthquakes at least[7]. Aftershocks are intentionally removed by the model developer when creating a historic catalogue of independent mainshock events, a process known as 'de-clustering' the historic event catalogue. The final stochastic event set thus represents independent mainshock activity but omits aftershock activity. This means that a chunk of seismicity capable of causing damage is missing from earthquake CAT models. In practice, this will only be a significant omission where aftershocks cause losses that approach or exceed those of the mainshock, a situation which, historically speaking, has been exceptional to date. Such cases can and do occur, however. One such exception was the February 22, 2011 earthquake near Christchurch, New Zealand, which GNS Science reports as an aftershock[8] of the September 4, 2010 Darfield earthquake. This caused one of the top five insured earthquake losses globally to date (US$17.2 billion; Swiss Re 2015).

Aftershocks look set to cause significant insured losses again in future. For example, an M_w>=6.0 aftershock located at or within 15 km from any of the multiple semiconductor manufacturing hubs in western Taiwan is likely to cause significant insured losses from non-structural property damage (e.g. vibration damage to semiconductor raw materials, stock, product and manufacturing equipment; occasional loss of clean room integrity), business interruption (BI) and contingent BI coverages. This scenario was inspired by the 1935 M_L7.1 Hsinchu–Taichung earthquake, which spawned a couple of aftershocks of magnitude M_L>=6.0, the largest of which reached M_L6.2 - 6.4. One of these, a M_L6.0 temblor, occurred about 15 km from the present day location of the Hsinchu Science Park (HSP). The HSP is likely to be the world's most valuable concentration of industrial property. RMS (2016) for example reported an estimate in excess of USD 319 billion of insured value at the HSP.

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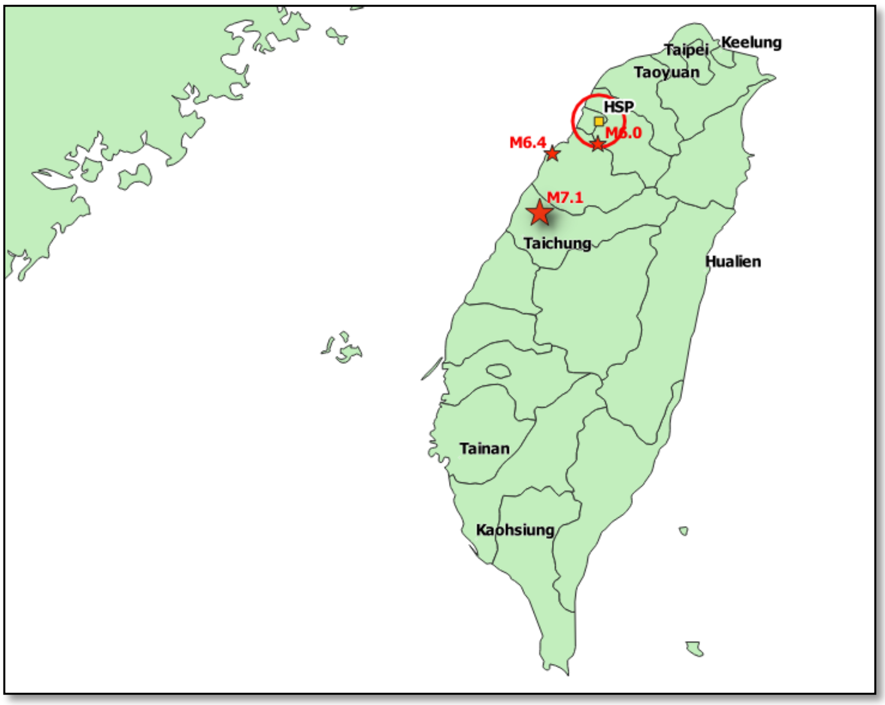
[7] Subduction megathrust earthquakes are an exception, aftershocks from which can be very large earthquakes in themselves.

[8] There is evidence that this event was triggered by stress changes caused by the earlier Darfield earthquake and hence could potentially be classified as either an aftershock or a triggered event. However, it is difficult to show that this event was going to occur anyway at some point in the future because it occurred on a previously unknown fault.

Figure 3. Locations of the two largest aftershocks (M6.0 and M6.4) following the M_L7.1 earthquake on April 21, 1935 in western Taiwan. One of these occurred within 15 km (red circle) of the present day location of the Hsinchu Science Park (HSP). Aftershocks were located using Fig. 1 from Lin et al. (2005).



As dependent events, the probability of a given aftershock is contingent on the probability of its parent mainshock and hence can be very low (e.g. only a few percent or less of the probability of the mainshock). This does not provide license for model vendors to ignore such events, however, because collectively the group of aftershocks can have a much larger damage footprint than the mainshock. The combined mainshock-aftershock footprint can potentially take a wide range of different geometries and will evolve over time, depending on the sequence of damaging aftershocks that occurs. This capability is not thought to be represented in any current vendor model, although it appears possible to do so (see below).

Industry challenges:

- *To develop a methodology for nesting a single sequence of damaging aftershocks under each qualifying mainshock event (e.g. those with a minimum magnitude of M_w7.0). Each sequence would comprise a small number (zero or more) of damaging aftershocks, each of which has a specified magnitude, depth, location and relative timing. One way to achieve this is by using a Period Loss Table (PLT), in which damaging aftershocks are assigned a position along a timeline within a fixed time period following the mainshock (e.g. 3 to 5 years). This is achievable with existing technologies and would in effect represent the simulated evolution of the combined mainshock-aftershock damage footprint over time.*

- *A more comprehensive solution would be to simulate multiple alternate sequences of damaging aftershocks beneath each qualifying mainshock event. This would be designed to capture the 100 or so most likely combinations of magnitude, depth, location and timing for damaging aftershocks. These sequences would need to be weighted by their relative probability; and then consumed by a modelling approach capable of processing multiple alternate loss outcomes under each mainshock event. A modelling framework with such an approach does not yet exist.*

4. Missing Fire Following the Earthquake (FFE) Models

Only a handful of FFE models currently exist, for territories that have either experienced major FFE events in the past century or so (Japan, California) or where the local authorities have proactively assessed the risk (e.g. New Zealand). FFE is most likely in residential settings and has been known to occur at the level of individual properties (2006 Pingtung earthquakes), city blocks and districts (1994 Northridge and 1995 Great Hanshin (Kobe) earthquakes) and citywide conflagrations (1906 San Francisco and 1923 Great Kanto earthquakes). Fortunately, citywide conflagrations today appear far less likely due to reduced use of wood frame[9] building construction; increased use of flame-retardant materials; better urban planning with enforcement of fire separation distances between buildings; and installation of automated mains gas shutoff valves in a few territories (such as Japan). This should reduce, but not eliminate, the risk of conflagration in these areas. One important factor governing the likelihood of conflagration is the presence of strong winds. Prevailing winds played a major role in the rapid spread of fire in both 20th century FFE conflagrations. Fire in the wake of the 1906 San Francisco earthquake spread rapidly under the influence of strong, warm, dry north-easterly winds known in northern California as both "Diablo" and "Santa Ana" winds. Similarly, the firestorm following the 1923 Great Kanto earthquake in Japan was spread by winds from a passing typhoon. Clearly, time of day (affecting likelihood of Diablo-type winds) and season (affecting typhoon occurrence) in which the earthquake occurs is an important factor to consider when associating strong winds with FFE events. To make matters worse, strong, convectional winds are also likely to be generated by the firestorm itself once it passes a certain size. Factors governing the incidence, spread and suppression of FFE are summarized in FEMA (2013) and USGS (2008).

Figure 4. San Francisco Earthquake of 1906: Ruins in vicinity of Post and Grant Avenue. Total destruction of several buildings that were left standing after the earthquake is evident. Source: Chadwick, H. D. / Public domain. https://commons.wikimedia.org/wiki/File:Post-and-Grant-Avenue-Look.jpg

[9] Wood frame is still commonly found in older (pre-1950) residential buildings in California, especially in San Francisco. It is also common in Tokyo's residential suburbs.

FFE is also likely to occur on a smaller scale in industrial manufacturing settings. Fire is very likely where spilt flammable fluids (e.g. paints, solvents, ruptured hydraulic oil lines) encounter toppled, sparking machinery or recently abandoned hot work (e.g. welds and oxy-acetylene torches, which can exceed 3,000°C in use). On-premises sprinklers may not work due to reduced (or no) mains water pressure and also are unlikely to be suitable for extinguishing oil and solvent based fires. Public fire brigades are unlikely to treat industrial areas with priority compared with the rescue of trapped civilians; and debris will also block road access. If fire occurs, it is likely to cause total loss of the industrial facility. It may also spready to adjoining industrial facilities if prevailing winds are strong and building separation distances are insufficient at these windspeeds to prevent bridging by burning *embers.*

Industry challenges:

- *In the first instance, to develop FFE models for densely populated, industrialised parts of earthquake-prone territories, such as Puerto Rico, Mexico, China, Taiwan, India, Pakistan, Indonesia, The Philippines, Turkey, Mexico, Colombia, Chile and Peru. Such models could use existing methods already used by model vendors for developing FFE models.*

- *Modelling of FFE initiation, spread and suppression requires multiple factors to be considered (e.g. day of week, time of day, prevailing winds, convectional winds, inter-building distances, etc.). Existing FFE models are unlikely to explicitly consider the full distribution of values these many factors can take. A more comprehensive approach is needed that effectively samples the multiple disparate distributions of these various factors and produces a subset of the 100 or so most likely outcomes, nested beneath a parent mainshock event judged likely to generate one or more initial fires. Each of these FFE outcomes would be weighted by their relative probability and, as with aftershocks, consumed by a modelling approach capable of processing multiple alternate loss outcomes nested under each mainshock event. Once again, a modelling framework implementing such an approach does not yet exist.*

5. Missing Tsunami Models

Tsunami loss models are currently available for Japan, the United States, Canada, Chile, Peru, Colombia, Ecuador, New Zealand, The Philippines, Taiwan and Indonesia (Sumatra). At least one model vendor also offers a tsunami inundation footprint catalogue that can be evaluated via their modelling platform. The majority of tsunami models available are for subduction megathrust-related tsunamis, in which a sudden large shallow rupture of the megathrust causes sudden deformation of the overlying sea surface, potentially triggering a tsunami. Some of these models appear quite sophisticated, involving hydrodynamic modelling of tsunami from source to onshore, for particular stochastic megathrust events. This is done by seeding a hydrodynamic offshore tsunami propagation model with parameter values describing the seabed displacement caused by the megathrust rupture. There is uncertainty in many of these parameters, so distributions of values are likely to be used rather than mean values. A second hydrodynamic model is then used to propagate the incoming tsunami waves onshore from a starting position about 10m offshore. Again, there is uncertainty in many of the parameters needed to seed this model, hence distributions are used here as well, rather than mean values. The end result of this is that a single megathrust rupture is capable of generating a distribution of alternative onshore tsunami inundation outcomes. How these are reduced to just one for use in the CAT model is not widely known at present, however.

Figure 5. "Boat on a house", Banda Aceh, Sumatra. The lives of more than 20 people were saved by this fishing boat as it was swept inland by the December 26, 2004 tsunami. It is now a monument to the disaster that killed 25,903 people in Banda Aceh alone (Doocy et al. 2007). © N. Winspear 2013.

Tsunami can also be caused by large, sudden submarine landslides, as happened in 1781/2 in southwest Taiwan; in Newfoundland in 1929; in Papua New Guinea in 1998; and in Indonesia in 2018 (in Sulawesi and western Java). Such tsunamis can be devastating to coastal populations because there is no time to issue and act on warnings because of the usually relatively short distance from slide to shore. The 1781/2 tsunami in Taiwan for example is reported to have killed up to 40,000 people (Li et al. 2015), making it the most devastating submarine landslide in historic times. Giant submarine landslide complexes have also been identified offshore from Brunei and on the southern China continental margin, which if, in the unlikely event that they occurred today, could cause serious humanitarian loss and property damage to countries bordering the South China Sea (Terry et al. 2017; Li et al. 2019; Zhu et al. 2019). The most common trigger for a submarine landslide is an earthquake, which can be of relatively low magnitude (e.g. M_w4 to 5), disturbing the stability of a sediment mass perched on an offshore slope. A submarine landslide can dynamically evolve in many different ways as it moves downslope, each variant of which could generate a range of alternate tsunami outcomes, each of which will in turn produce a distribution of damage. A single submarine landslide could therefore generate a wide range of tsunami outcomes and an even wider range of damage outcomes. Needless to say, current efforts are limited to only a handful of inundation footprints from submarine landslides, representing the most likely tsunami outcomes calculated by hydrodynamic simulation. No fully probabilistic models yet exist.

Industry challenges:

- *In the first instance, to develop 'most likely' tsunami inundation footprints from earthquake-triggered submarine landslides in the following major tectonic settings, using existing tools, techniques and technologies:*
    - *For tectonically passive (quiet but not inactive) offshore continental shelves, such as the north-eastern seaboard of the United States and Canada; and the south China margin.*
    - *For tectonically active subduction-related accretionary complexes[10], including those located landward of the Japan trench, the Sagami and Nankai troughs;*

[10] An accretionary complex or 'prism' forms as sediment is scraped off the subducting oceanic slab as it subducts.

the Cascadia subduction zone; and the Kaoping slope, southwest Taiwan. Several of these have experienced major submarine landslides in historic times (e.g. Li et al. 2015; Tappin et al. 2014).

- *As for simulation of aftershocks and FFE, the bigger challenge here is to develop a modelling approach that allows the nesting and subsequent loss modelling of multiple (100+) alternate alternative tsunami outcomes beneath each megathrust rupture or submarine landslide.*

Conclusions

Recurring themes in this paper include opportunities for model development and development of new capability to process many alternate loss outcomes per stochastic event. These are summarised here:

1) **Modelling opportunities:**
   (a) There are significant gaps still waiting to be filled in the current model landscape. Fortunately, missing FFE models and tsunami inundation footprints from submarine landslides can be created using currently available tools, techniques and technologies. There are no technological barriers to doing so.

   (b) The other major immediately outstanding modelling opportunity is to develop a suite of 'single site' CAT models capable of analysing individual properties. Such models do not currently exist to the best of the author's knowledge. This requires development of catalogues of individual property damage functions for a range of common higher-valued property types (suggest beginning with the United States). This in turn needs expertise in civil and structural engineering, seismology/ wind engineering and CAT loss modelling. Once such tools are available, they can be used by the (re)insurance industry to properly assess PML at the scale of individual properties that are not part of a larger portfolio of similar properties.

2) **Modelling of Alternate Secondary Peril Outcomes:** A significant revision is proposed for the architecture of CAT modelling frameworks to enable them to process alternate secondary peril loss outcomes nested beneath each stochastic loss event. For example, a large megathrust earthquake may produce one distribution of damage from ground shaking, together with multiple damage distributions from tsunami and FFE. There could for example be 10,000 different combinations[11] of loss outcomes for this event, each with a different distribution of damage. Not all secondary perils are relevant in all cases, hence in a crustal earthquake (such as a rupture of the San Andreas fault in California) the tsunami peril would be replaced with that of aftershocks, producing a similar number of loss outcome combinations. These outcomes would need to account for double counting of damage between the primary and secondary perils; after which they could be sampled to reduce them to a manageable number (e.g. 100). This would of course increase model runtime, so new optimization strategies to counter this would also be needed. These alternate loss outcomes could then be aggregated either into a single damage distribution or into a probability-weighted loss value that can be carried forward into the existing loss calculation processing. As today, this would result in a single loss EP curve that can be consumed by the (re)insurance

[11] Each of the tsunami and FFE outcomes needs to take account of all other outcomes from the other secondary peril, hence in this example there would be 1 mainshock x 100 FFE x 100 tsunami = 10,000 combined peril outcomes.

industry. The key benefit of this approach is that it represents a fully probabilistic view of alternate primary and secondary peril outcomes in a single loss EP curve. No CAT model currently in existence offers such comprehensive packaging of integrated primary/ secondary peril, multi-outcome results[12]. Finally, whilst this paper has focussed on earthquake-related perils, there is no reason why this approach could not also be applied to atmospheric perils, e.g. modelling of numerous alternate hurricane-related wind, storm surge, wildfire and inland flood loss outcomes.

The future certainly appears bright in the world of CAT modelling. Innovation looks to be just around the corner, our task being to point out where challenges and opportunities exist, to assist, guide and, where possible, speed this along, regardless of current technological limitations. The ideas presented here could represent significant opportunities for model vendors. It will be interesting to see who goes and first makes them a reality.

[12] It is commonly argued that existing CAT models do consider alternate loss outcomes because they consider the combined secondary uncertainty of the primary and secondary perils. Whist this is the case to some extent, there is usually only one secondary peril outcome (e.g. one FFE or tsunami footprint) considered per stochastic event. What is being outlined here is representing many alternate secondary peril outcomes nested beneath each stochastic event. These are jointly far more likely to represent the loss variability that is possible across the range of primary-secondary peril combinations than a single primary-secondary peril combination alone.

References

1. ATC-13 (1985) Earthquake damage evaluation data for California. Applied Technology Council, 492p.

2. ATC-13 (2002) Commentary on the use of ATC-13 earthquake damage evaluation data for probable maximum loss studies of California buildings. Applied Technology Council, 66p.

3. Doocy, S. Gorokhovich, Y., Burnham, G., Balk, D. & Robinson, C. (2007) Tsunami mortality estimates and vulnerability mapping in Aceh, Indonesia. *American Journal of Public Health*, **97** (Supplement 1), S146-S151.

4. FEMA (2013) Hazus®-MH 2.1 Earthquake Model Technical Manual. https://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf

5. Li, L., A. D. Switzer, Wang, Y., Weiss, R., Qiu, Q., Chan, C.H. & Tapponnier, P. (2015) What caused the mysterious eighteenth century tsunami that struck the southwest Taiwan coast? *Geophysical Research Letters*, **42**, 8498-8506. hhttps://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL065567

6. Li, L., Shi, F., Ma, G. & Qiu, Q. (2019) Tsunamigenic Potential of the Baiyun Slide Complex in the South China Sea. *Journal of Geophysical Research: Solid Earth*, **124**. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB018062

7. Lin, Y.N.N., Chen, Y.G., Wu, Y.M., Wang, Y., Yang, K.M. & Ota, Y. (2005) Surface deformation and seismogenic structure model of 1935 Hsinchu-Taichung earthquake (MGR=7.1), Miaoli, northwestern Taiwan. *Hokudan International Symposium on Active Faulting 2005*. http://active.gl.ntu.edu.tw/People/Students/Nina/aboutme/conf/2005Hokudan.pdf

8. RMS (2016) Understanding Risk Accumulations in Taiwan's Science Parks. https://www.rms.com/blog/2016/12/19/understanding-risk-accumulations-in-taiwans-science-parks/

9. Swiss Re (2015) Small quakes, big impact: lessons learnt from Christchurch. https://www.swissre.com/dam/jcr:57469cc6-0a23-4100-8fe4-00663af35ad0/lessons_from_christchurch_web.pdf

10. Tappin, D.R., Grilli, S.T., Harris, J.C., Geller, R.J., Masterlark, T., Kirby, J.T., Shi, F., Ma, G., Thingbaijam, K.K.S. & Mai, M. (2014) Did a submarine landslide contribute to the 2011 Tohoku tsunami? *Marine Geology*, **357**, 344-361. https://www.sciencedirect.com/science/article/pii/S0025322714002898?via%3Dihub

11. Terry, J.P., Winspear, N.R., Goff, J. & Tan, P.H. (2017) Past and potential tsunami sources in the South China Sea: A brief synthesis. *Earth Science Reviews*, **167**, 47-61. https://www.sciencedirect.com/science/article/pii/S0012825216302902?via%3Dihub

12. USGS (2008) The Shakeout Scenario: Supplemental Study. Fire Following Earthquake. https://www.sparisk.com/documents/Scawthorn-2008-ShakeOut-FFE.pdf

13. Zhu, C., Cheng, S., Li, Q., Shan, H., Lu, J., Shen, Z., Liu, X. & Jia, Y. (2019) Giant submarine landslide in the South China Sea: Evidence, Causes, and Implications. *Journal of Marine Science and Engineering*, **7**, 152; doi:10.3390/jmse7050152.

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