AIR'S UPDATED VIEW OF EARTHQUAKE RISK IN CHILE

INTRODUCTION

On February 27, 2010, an M8.8 earthquake struck about 8 km off the coast of Chile's Maule region at a focal depth of 35 km, rupturing 500 km of the Nazca subduction zone. Intense shaking lasted about three minutes and was felt over a large area, making it one of the most damaging earthquakes in recent years.

Chile occupies an extremely long and narrow strip along the west coast of South America. Roughly 80% of the total replacement value of Chile's residential, commercial, and industrial exposure is located within the central part of the country, where the Maule earthquake occurred. Large magnitude earthquakes in this region have caused considerable damage and financial loss in the past. While powerful earthquakes can occur in other areas, they tend to cause comparatively little damage because they affect much less exposure. The M8.3 earthquake that struck near Illapel (about 300 km north of Santiago) in September 2015 is a good example.

Earthquake risk in Chile is driven primarily by large subduction zone interface events occurring along the coast on the Nazca plate. The shape of the country, the distribution of exposure within it, and the geometry of the Nazca plate create a unique seismic risk profile. Figure 1 shows the tectonic context of Chile, where the Nazca plate is moving (subducting) beneath the South American plate. Strain accumulates in areas where this relative motion becomes locked due to anomalies in the earth's crust—until an earthquake releases the built-up energy.

Where there is sufficient data, scientists adopt a time-dependent (TD) view of earthquake hazard in which the probability of a rupture depends on when the last large-magnitude event occurred in that region.

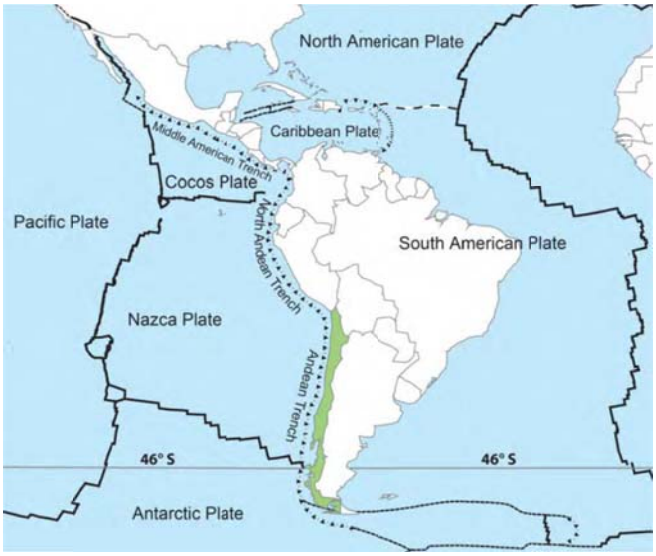

Figure 1. Tectonic context of Chile.

According to a TD view of risk, the occurrence of the 2010 Maule earthquake significantly reduced the probability of another large earthquake in the same area within the next few years. Furthermore, considering the Maule earthquake's proximity to high concentrations of exposure in Chile, it significantly reduced the probability of large losses on a countrywide basis.[1]

Thus the AIR view of the significant reduction in the probability of another Maule-type earthquake occurring in the same area is consistent with well-established and well-accepted TD models of earthquake occurrence. For example, Japan's Headquarters for Earthquake Research Promotion (HERP)—the main organization responsible for formulating earthquake risk in Japan—has set a zero probability for another Tohoku-type earthquake within

[1] By comparison, were an event of similar magnitude to occur in Colombia, the impact on the probability of future losses would not be as great. Risk in Colombia is driven by a more widely distributed range of seismic sources, including both crustal faults and the Nazca subduction zone, and exposures are more uniformly distributed.

the Japan Trench for the 30 years following that 2011 event.

This issue brief discusses the impact of the Maule earthquake on earthquake risk in Chile in the context of AIR's newly updated earthquake risk models for South America. It also provides an overview of the advanced science and technology AIR used to formulate the earthquake hazard in Chile.

SEISMIC HAZARD

The subduction of the Nazca plate beneath the South American plate at the Nazca trench constitutes the longest subduction zone in the world and has generated some of the largest magnitude earthquakes ever recorded. Earthquakes here do not generally occur as a single large rupture that releases all accumulated stress within the fault segment. Instead, what typically occurs is a series of several smaller, overlapping ruptures of different magnitudes, with each event discharging only a portion of the stress built up on the fault. Such earthquakes can also change the local state of stress, influencing the probability of rupture on neighboring sections of the subduction interface.

The complexity of the Nazca subduction zone makes the use of traditional time-dependent rupture forecast models difficult and potentially inaccurate. In their simplest form, TD rupture forecasts identify the dominant so-called "characteristic" earthquake on a segment of subduction zone, construct density functions for the time interval between such earthquakes, and estimate a conditional probability of occurrence using the time since the last occurrence of a similar magnitude earthquake.

While progress has been made in improving the reliability of this commonly used procedure by better quantifying and accounting for model and parametric uncertainties, it is nevertheless designed for single-mode rupture—that is, a single characteristic earthquake on a single, discrete segment of a subduction zone. For the 2015 update to the earthquake models for South America, AIR enhanced the classic TD rupture forecast model to take into consideration the more complex locking and coupling of different areas of the Nazca subduction zone and the impacts of past large earthquakes on estimating the rupture probability of future earthquakes.

The hazard in the AIR Earthquake Model for Chile is represented by a 10,000-year stochastic event catalog. To generate the catalog, earthquakes are simulated source zone by source zone (Figure 2). It should be noted that time dependence can meaningfully be estimated only for well-studied faults or zones for which there is abundant slip rate or paleoseismic data. In the case of Chile, a time-dependence model is applied to the subduction zone segments whose rupture histories are well-known. Crustal faults and background seismicity are modeled as time-independent (TID). Thus the model's final stochastic catalog represents a combination of both time-dependent and time-independent catalogs. A purely TID catalog was developed for internal testing purposes, including the analyses shown in this issue brief.

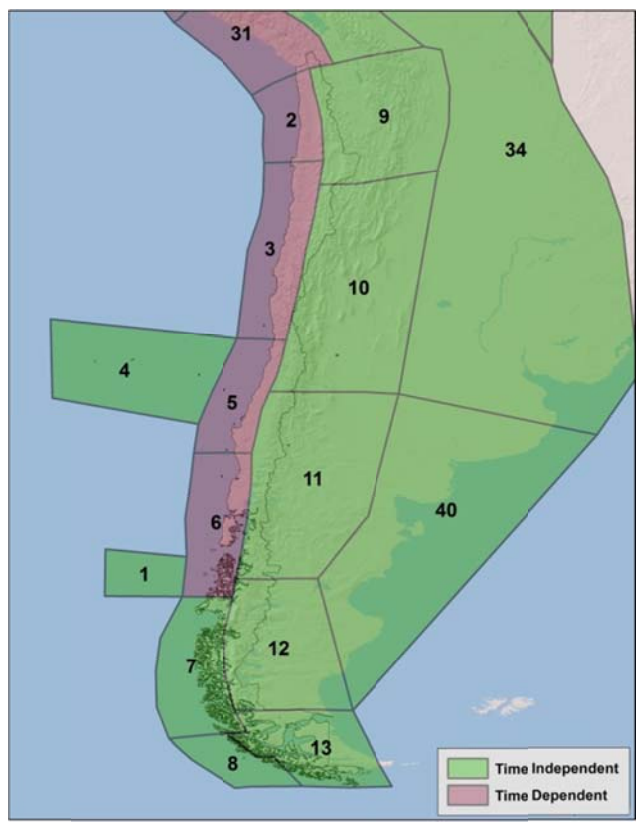

Figure 2. AIR seismic source zones for Chile. The Maule earthquake occurred in Seismic Zone 5. (Source: AIR)

The magnitude-frequency distributions for AIR's 10,000-year TD stochastic catalog, the 10,000-year TID stochastic catalog, and the historical catalog for the deep and shallow trench portion of Seismic Zone 5—within which the Maule earthquake occurred—are shown in Figure 3.

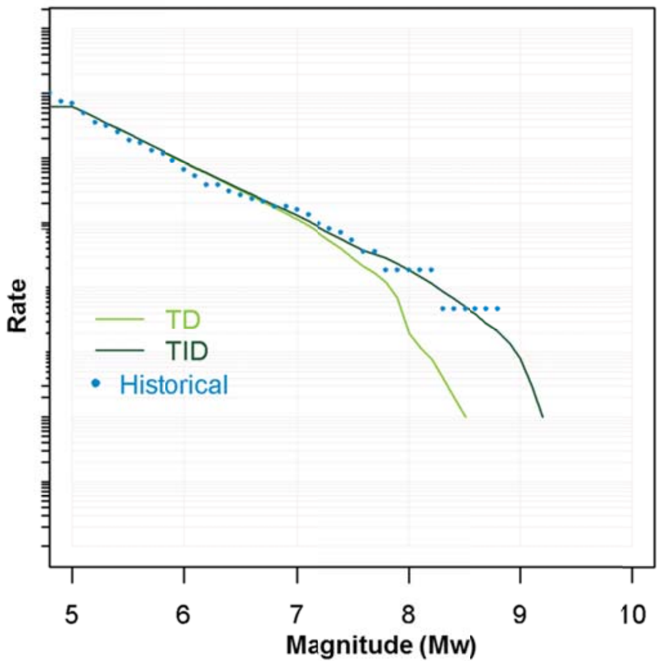

Figure 3. Magnitude rates of historical seismicity (blue points), time-dependent simulated seismicity (light green curve), and time-independent simulated seismicity (dark green curve) in Seismic Zone 5. (Source: AIR)

The TD magnitude rate distribution reflects a significant reduction in the probability of large Maule-type earthquakes for this zone as a result of the release of stress by the 2010 Maule rupture. This assumption is consistent with scientific understanding of long-term strain accumulation and rupture processes.

THE MAULE EARTHQUAKE

The 2010 M8.8 Maule earthquake ruptured bilaterally with two major areas of slip, as depicted in Figure 4. The stronger of the two produced about 15–20 m of peak slip and was located in the northern part of the rupture area. The northern extent of the rupture zone overlaps the slip area from a 1928 M7.8 rupture and reaches the southern edge of a 1985 M7.9 earthquake rupture plane below the Juan Fernandez Ridge. In fact, aftershocks from the Maule earthquake spread well within the 1985 rupture zone. The southern area experienced a peak slip of 10 m. The southern extent of the rupture zone extended to the northern edge of the 1960 M9.5 earthquake—the largest instrumentally recorded earthquake in history—with some overlap.

Figure 4 shows the Maule coseismic slip distribution—that is, the relative displacement of formerly adjacent points on the fault plane that occurred *during* the earthquake.

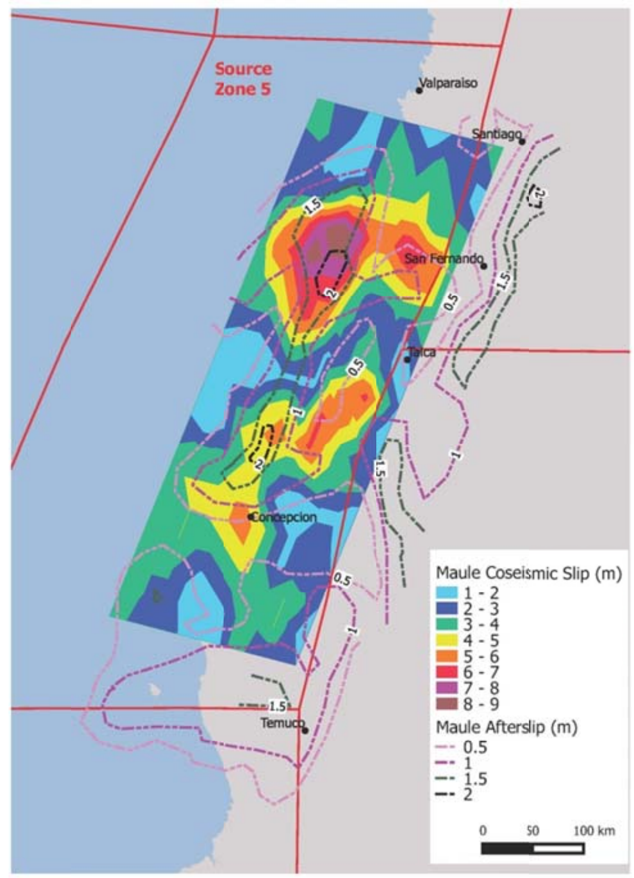

Figure 4. Maule coseismic slip distribution and the distribution of the aftershocks. (Sources: AIR; Lange et al.)

Using 1835 as the date of the last Maule-type earthquake before the 2011 rupture, the reported peak coseismic slip values are consistent with the expected slip *deficit* in this section of the Nazca subduction zone—consistent, that is, with the amount of strain that would be expected to accumulate over that period. In particular, assuming a rate of convergence between the Nazca and South America tectonic plates of about 7–8 cm per year and assuming the plates were completely locked, the expected slip deficit since 1835 would have been expected to be about 12–14 m at the time of the Maule rupture—a figure well within the overall range of the reported coseismic slip. Indeed, the potential for just such a large earthquake in this region had been captured in AIR's previous version of the model.

After a large earthquake, or mainshock, the accumulation of strain continues to be released in the form of aftershocks and *aseismic* slip—or smooth movement that does not produce seismic shocks. Lin et al. 2013 and Lange et al. 2014 conducted an investigation into this postseismic slip distribution within the Maule subduction zone. Findings show a broad region of up to 2 meters of postseismic slip with some aftershocks at the periphery of the rupture area. About 90% of the postseismic deformation has been aseismic—roughly equivalent to a "slow" earthquake of M8.34–8.44. The contours in Figure 4 show the spatial distribution of the postseismic slip (afterslip) found by Lange et al.

The large coseismic and the broad postseismic slip within the Maule rupture area indicate that this segment of the Nazca subduction zone is now in a relaxed state and slowly readjusting to the impact of stress changes from the Maule mainshock. There are almost certainly areas at the periphery that did not fully rupture, and these may retain some unrealized strain accumulation. These areas have been—and will continue to be—prime candidates for causing further aftershocks. However, any such aftershocks are unlikely to trigger another Maule-type earthquake in the same area for a considerable time to come because there is now little accumulated strain energy within the Maule main rupture zone.

LOSSES

In addition to the changes in seismicity, the distribution of exposure in Chile is a critical factor in determining the impact of the Maule earthquake on the country's exceedance probability (EP) curve.

According to AIR's detailed industry exposure database (IED)—which contains up-to-date information on risk counts, replacement values, and building construction and occupancy characteristics derived from local sources and remote sensing—the replacement values of all residential, commercial, and industrial risks in the CRESTA zones affected by the earthquake together account for 80% of the total exposure value in the entire country. The elongated shape of the country, the concentrations of exposure within it, and the location of the Maule rupture play critical roles in the reduction of seismic risk in Chile after the Maule event.

Figure 5 compares loss exceedance probability curves for AIR's TID and TD stochastic catalogs. The losses are based on an "all properties" exposure database that includes uninsurable buildings, such as adobe, in addition to insurable buildings to enable a more reasonable comparison with observed losses.

AIR's earthquake model for Chile explicitly accounts for tsunami losses with a separate tsunami module. However, tsunami is only supported for AIR's TD catalog. Therefore, Figure 5 shows EP loss curves for the TID catalog without the contribution of tsunami to losses and the TD catalog with and without tsunami.

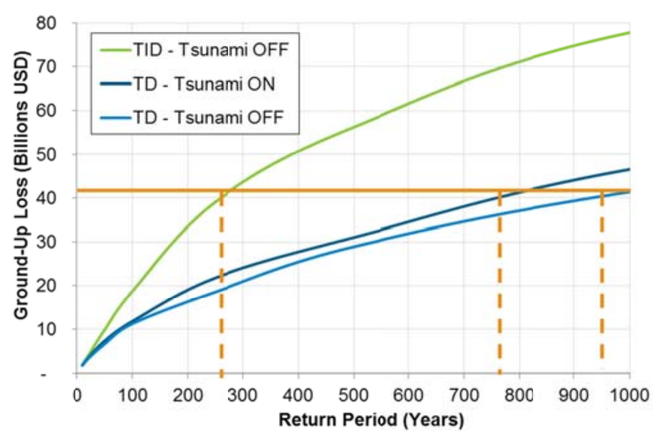

Figure 5. EP curves for TID and TD (with and without tsunami) stochastic catalogs.(Source: AIR)

Figure 5 also shows the ground-up modeled losses for the 2010 Maule earthquake (about USD 42 billion) and the corresponding return periods. For the *time-independent* view, the 2010 Maule modeled loss (trended to 2015 values) corresponds to about the

250-year return period, or 0.4% exceedance probability. Using the *time-dependent* perspective, the Maule loss corresponds to the 750-year return period with tsunami and the 950-year return period without tsunami losses. As can be seen from Figure 5, the new (post-Maule) TD catalog results in a significantly reduced view of risk compared to the TID catalog.

The two analyses described below help to more fully illustrate the impact of Chile's exposure distribution on the view of risk in the new TD catalog, and the significant reduction in earthquake risk post-Maule.

TEST 1: UNIFORM EXPOSURE

In this analysis, the impact of time-dependency—that is, the impact of the Maule earthquake on seismic risk in Chile—is evaluated using both AIR's detailed IED and a uniformly distributed contrived exposure set as illustrated in Figure 7. As is immediately visible, the actual industry exposure is concentrated in the cities, particularly in the region between Santiago and Concepción. On the right-hand side of Figure 7, the value of the contrived exposure set is uniformly distributed throughout the country.

Figure 6 shows the normalized loss exceedance probability curves for the IED and uniformly distributed contrived exposure for both TD and TID catalogs. In order to show the modeled losses in the same plot, they have been normalized as a percentage of the total exposure value, for both the IED and the contrived exposure, and tsunami losses were excluded. The blue solid and dotted lines show the TD EP curves for the IED and uniformly distributed exposure, respectively. The green solid and dotted lines show the corresponding EP curves created using the TID catalog.

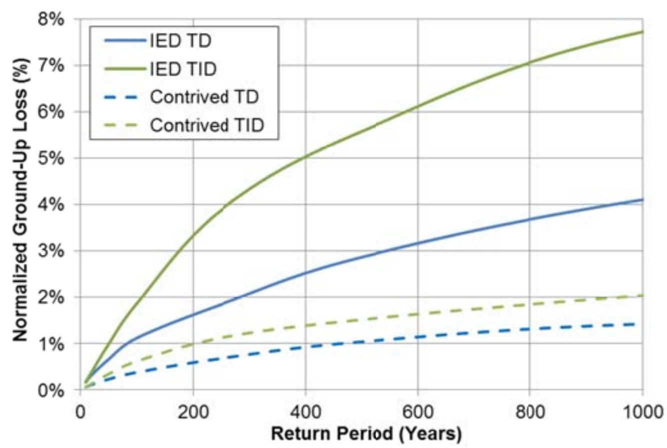

Figure 6. The impact of time-dependency on IED versus uniformly distributed contrived exposure. (Source: AIR)

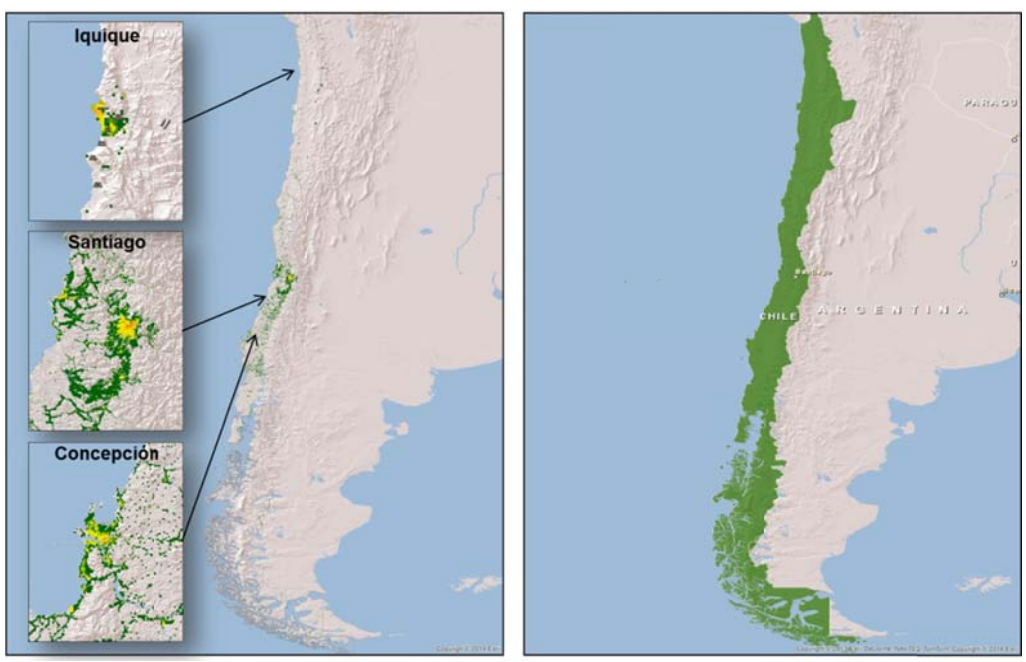

Figure 7. AIR's IED (left) and uniformly distributed contrived exposure (right). (Source: AIR)

Comparing the IED and contrived exposure curves, it is evident that the maximum loss ratios for the 1,000-year return period are significantly higher for the actual IED (8%) than for the contrived exposure (2%). This is a direct consequence of the exposure distribution. The losses for the contrived exposure plateau at a relatively low loss ratio because of the uniform distribution along the country; there are no events in the catalog and indeed no scientifically plausible events of a magnitude high enough to impact the entire country given that Chile occupies such a long strip of land. Due to its elongated footprint and considerable size, even the 1960 M9.5 Valdivia earthquake—the largest ever recorded—impacted only a portion of the country. The second, even more important observation from Figure 6 is that the difference between the TD and TID curves is significantly more pronounced for the IED compared to the contrived exposure. This shows the importance of Chile's exposure distribution on the impact of time-dependency. The large concentration of exposures in the Santiago area is responsible for the difference between the TD and TID curves in the IED-based results. This finding is borne out by Test 2.

TEST 2: REMOVING STOCHASTIC EVENTS

The second analysis tests the hypothesis that the time-dependent view adopted by AIR has shifted the EP curve too far, reducing by too much the probability of another Maule-size loss in the near future. Although it is clear from observation data that Seismic Zone 5, where the Maule earthquake occurred, is currently in a relaxed state—incapable of producing another large event in the foreseeable future—could the Maule earthquake have transferred stress to an adjacent seismic zone, making it more likely to rupture? Furthermore, if an adjacent zone were in fact to rupture, could it produce losses as large as Maule's?

To take the more conservative view, this analysis uses the TID catalog as the reference catalog. By removing large subduction zone events from the catalog, zone by zone, we can effectively simulate the post-event impact on the EP curve of a large earthquake occurring. As shown in the exhibits below, because 80% of the total replacement value of Chile's residential, commercial, and industrial exposure is located within the central part of the country between Valparaíso and Santiago to the north and Concepción to the south, large subduction zone events outside of Seismic Zone 5 have little impact on modeled losses.

The spatial distribution of stochastic events by magnitude in AIR's TID catalog is shown in Figure 8.

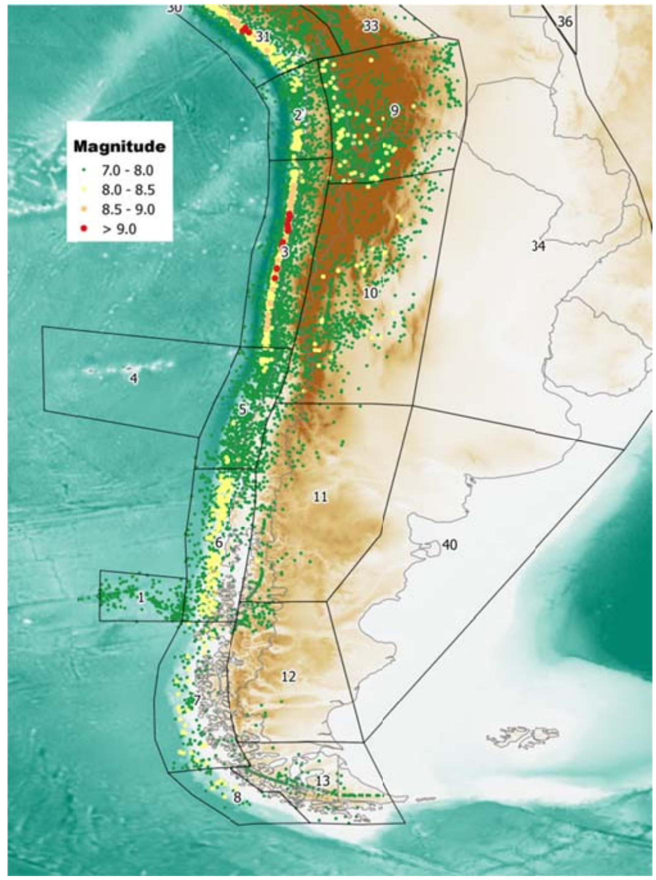

Figure 8. Spatial distribution of stochastic events by magnitude in the 10,000-year time-independent stochastic catalog. (Source: AIR)

AIR Seismic Zone 2

Removing subduction zone events from Seismic Zone 2 has minimal impact on both test exposures (Figure 9). Indeed it is difficult to discern the difference in the EP curves since they very nearly lay on top of each other. For the IED, this near zero impact is due to the relatively sparse exposure in this zone. Thus if the Maule earthquake transferred stress to Seismic Zone 2, the impact of a rupture would be minimal.

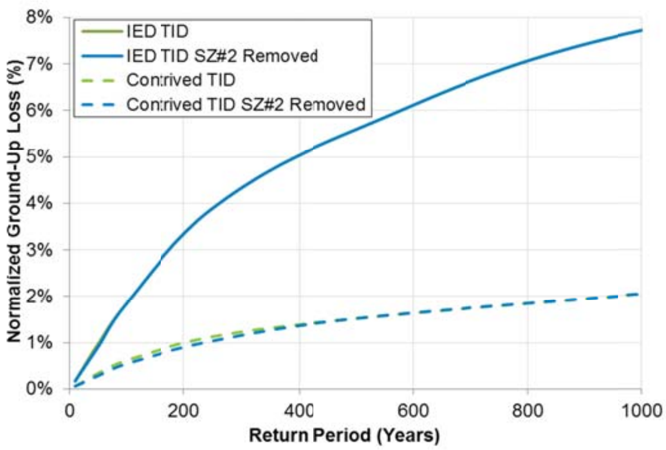

Figure 9. Seismic Zone 2 subduction zone events removed from the TID catalog. This removal has minimal impact on both test exposures. For the IED, the absence of change (the blue solid line obscures the green solid line) is due to the relatively small exposure affected in this zone. (Source: AIR)

AIR SEISMIC ZONE 3

Removing subduction zone events from Seismic Zone 3 has minimal impact on the contrived exposure EP curve (Figure 10). For the IED, the impact is more pronounced, but still comparatively small due to the relatively low value of affected exposure in this zone. Thus if the Maule earthquake transferred stress to Seismic Zone 3, the impact of a rupture would be small.

Figure 10. Seismic Zone 3 subduction zone events removed from the TID catalog. (Source: AIR)

AIR SEISMIC ZONE 5

Removing subduction zone events from Seismic Zone 5—the zone in which the 2010 Maule earthquake actually occurred—has minimal impact on the contrived exposure EP curve (Figure 11). For the IED however, the impact is significant due to the concentration of exposure in this zone. But the 2010 Maule earthquake itself effectively removed other large events in this zone for the foreseeable future.

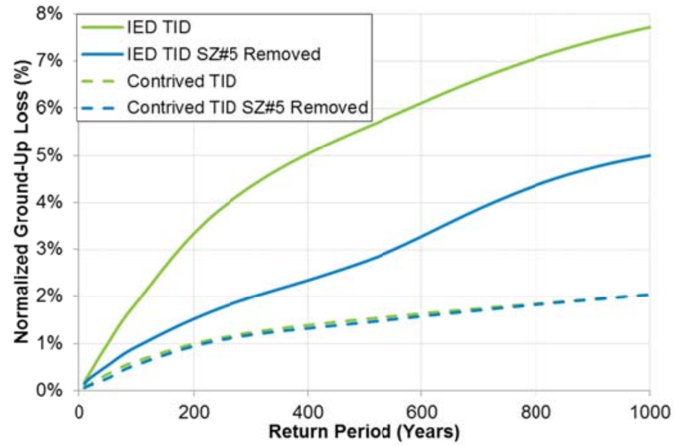

Figure 11. Seismic Zone 5 subduction zone events removed from the TID catalog. (Source: AIR)

AIR SEISMIC ZONE 6

Removing subduction zone events from Seismic Zone 6 has minimal impact on both test exposures (Figure 12). For the IED, the minimal impact is due to the relatively sparse exposure in this zone. Thus even in the case that the Maule earthquake transferred stress to Seismic Zone 6, the impact of a rupture there on modeled losses would be small.

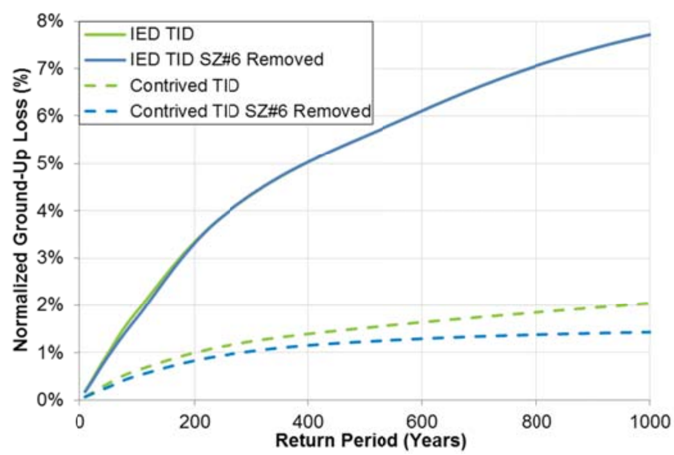

Figure 12. Seismic Zone 6 subduction zone events removed from the TID catalog. (Source: AIR)

CONCLUSION

Our studies have revealed that there are three important factors in the significant reduction of seismic risk in Chile after the 2010 Maule rupture:

- The location of the earthquake itself
- The shape of the country
- The distribution of the exposure within the country

Although large magnitude (M8–M8.5) events do occur relatively frequently along much of Chile's coast, there is generally little exposure at risk from these events. Of the exposure at risk in the country, 80% lies within CRESTA zones impacted by events occurring within AIR Seismic Zone 5, the seismic zone in which the Maule earthquake occurred and released the accumulation of stress.

After the 2010 Maule earthquake, a wealth of data became available that enabled better and broader assessment of seismic risk in South America, and informed the 2015 update to AIR's earthquake models for Chile and the wider region. AIR validated modeled loss results with rigorous internal processes and under the scrutiny of external independent experts to ensure that final model results made sense. Given the importance of risk assessment to the local and global insurance industries exposed to earthquake risk in Chile, AIR is dedicated to providing clients the best view of risk as well as a clear understanding of the inner workings of the models.

The reduction of risk in Chile reflected in the updated AIR model is almost exclusively attributable to the significant release of stress within AIR Seismic Zone 5 after the Maule rupture, rather than to changes in modeling methodology. It is important to keep in mind, however, that due to the nature of time dependency, output from a TD model provides a view of risk only for a limited number of years into the future. Ultimately, seismic stress in the area impacted by the Maule earthquake will begin to slowly accumulate once again.

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