The AIR Earthquake Model for the Caribbean

In early January 2020, a series of earthquakes—one of them an M6.4—struck southwestern Puerto Rico, causing damage and disruption to the whole island. Later that month, an M7.7 earthquake occurred just 80 miles southwest of the Cayman Islands and 72 miles northwest of Hanover, Jamaica. These recent quakes highlight the need to manage the risk in this highly active, complex seismic region.

AIR

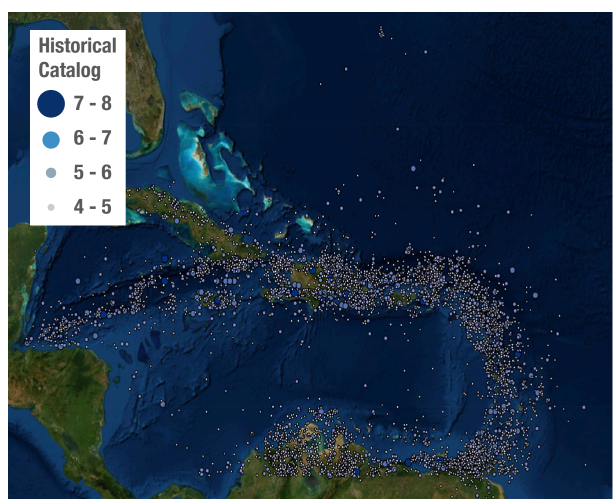
The Caribbean region has the potential to generate large, destructive earthquakes. The 2010 M7.0 Haiti earthquake, for example, leveled Port-au-Prince, destroyed homes and infrastructure, killed hundreds of thousands, and caused billions in economic loss. But even moderately large earthquakes can be devastating.

The AIR Earthquake Model for the Caribbean delivers an integrated view of loss from ground shaking, liquefaction, and tsunami for 29 countries. The model incorporates the latest paleoseismological data and provides a time-dependent view of seismicity that accounts for the buildup of strain on large, well-studied faults over time, offering the most realistic view of seismic hazard available for the region. Combined with detailed Industry Exposure Databases, the model delivers a comprehensive view of Caribbean earthquake risk necessary for effective risk management.

Latest Science and Advanced Modeling Technologies Integrated with Time-Dependent Modeling Yields Most Comprehensive, Realistic View of Hazard

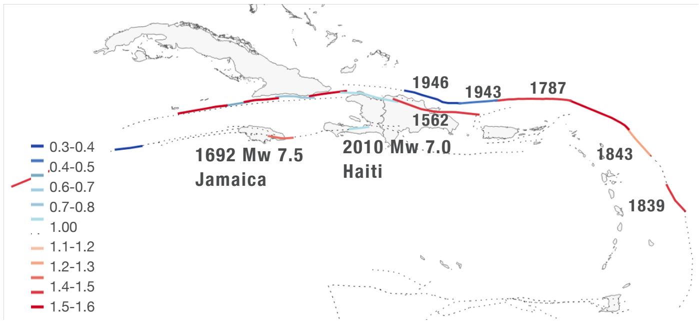
AIR has employed an innovative approach to modeling time-dependent seismicity that incorporates a historical earthquake catalog compiled from both local and global sources that is homogenized to moment magnitude—the most reliable measure of earthquake size—and active fault information from GPS data, paleoseismic studies, marine surveys, strain and moment rates from kinematic modeling of GPS survey data, and regional tectonics.

A robust seismicity model, especially for regions such as the Caribbean where seismicity is moderate to low, requires additional information to complement the short historical record, so AIR compiled a fault database with detailed information to inform the location and frequency of large, infrequent earthquakes. Strain and moment rates from kinematic modeling provide additional constraints on the rate of large magnitude earthquakes in various areas to minimize the impact of uncertainty on fault data and historical seismicity data. The kinematic modeling results of GPS data also provide insights into the status of fault coupling or the rate of seismic energy accumulation along subduction zone faults, which improves the accuracy of the estimation of frequency for large magnitude earthquakes. Integration of these different types of data is essential for a comprehensive, self-consistent seismicity model and is more robust than a seismicity model built on any single set of data or a simple combination of models using individual data sets with a simple logic tree.



Historical seismicity in the Caribbean by magnitude (Mw ≥ 4).

Most time-dependent models follow the elastic rebound hypothesis, which states that the Earth's crust can gradually store elastic stress that is released suddenly during an earthquake. As the fault accumulates strain, earthquake likelihood increases. The difficulty in applying this concept to forecasting large earthquakes on subduction zones, however, can be a lack of information about levels of stress buildup along different sections and variations in rupture magnitude due to the complexity of fault geometry—with fault segments that may be fully locked, partially locked, or relaxed. The AIR Earthquake Model for the Caribbean considers well-constrained historical ruptures and fault segmentation to provide a realistic view of rupture and magnitude probability.



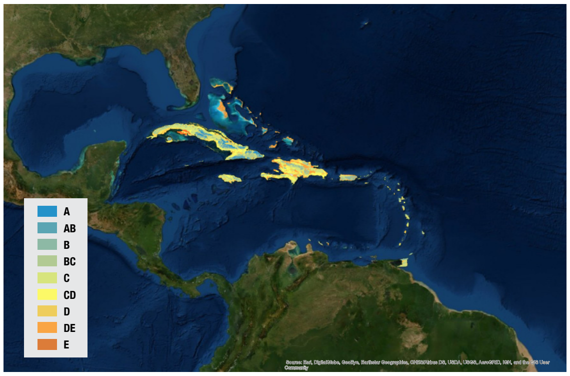
The time-dependent AIR Earthquake Model for the Caribbean considers the buildup of strain on faults over time, which affects the likelihood of future ruptures and their potential magnitudes. Warmer colors indicate increased probability of rupture when compared to a time-independent model, and cooler colors indicate decreased probability of rupture.

Modeling Complex Multi-Fault Rupture Scenarios

Since the 2010 Haiti earthquake, seismometers, accelerometers, and GPS recording stations have been installed and field surveys have been performed to understand the fault geometries at work both on land and offshore. These new fault data along with a more comprehensive understanding of the tectonics of the Caribbean region overall allow researchers to better identify faults that may rupture in multi-segment ruptures. This is especially important when modeling complex subduction zones such as the Puerto Rico Trench and Lesser Antilles, where the entire subduction zone is made up of fault segments and large earthquakes are possible along sequences of neighboring segments in multi-fault rupture scenarios.

High-Resolution Soil Maps Capture Detailed Shaking Intensity and Liquefaction Risk

Soil type can dramatically alter the intensity and nature of ground shaking. AIR developed detailed soil maps for the Caribbean from various data, including high-resolution geological data, aerial imagery, and digital topographic slope data. These soil maps use a 250-meter base map for the entire model domain, the resolution of which is as fine as 30 meters for large population centers to accurately account for risk variation due to the impact of soil type.

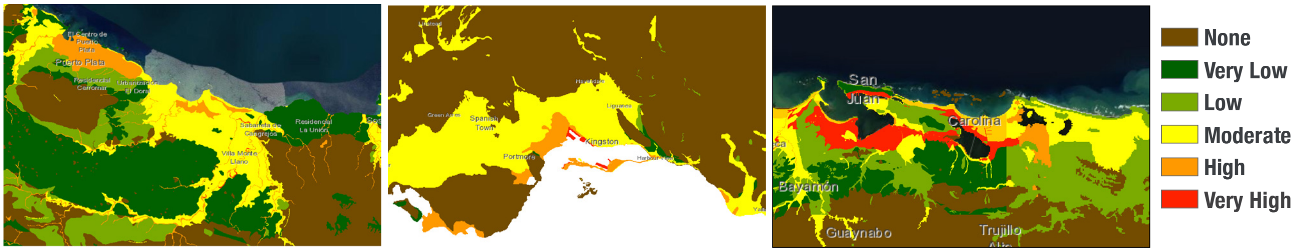


AIR developed high-resolution soil maps of up to 30 meters to accurately account for risk variation due to the impact of soil type.

Modeling ground motion footprints for various types of earthquakes in the Caribbean requires a good understanding of the regional geological, geophysical, and tectonic environment and the types of earthquakes that can occur. Based on detailed analysis of the tectonic environment, AIR developed a ground motion model for each type of earthquake in the Caribbean from the latest ground motion prediction equations developed for tectonic environments similar to the Caribbean region.

Explicit Modeling of Liquefaction

Liquefaction occurs when intense ground shaking causes loose coarse-grained soil at or near the ground surface, which has poor drainage and is saturated with water or is unconsolidated, to lose its strength, causing the soil to behave as a liquid that is unable to support weight. Buildings can suddenly tilt or even topple, and buried utility lines, pipelines, and ducts can rupture, significantly increasing potential damage and losses. In the Caribbean,



Modeled liquefaction susceptibility for Dominican Republic (left), Jamaica (center), and Puerto Rico (right) show high susceptibility, especially along the coast and in ports where land reclamation is a popular practice.

many islands have expanded their coastlines through land reclamation, a process that creates new land from the seabed often using dredged materials that are poorly consolidated.

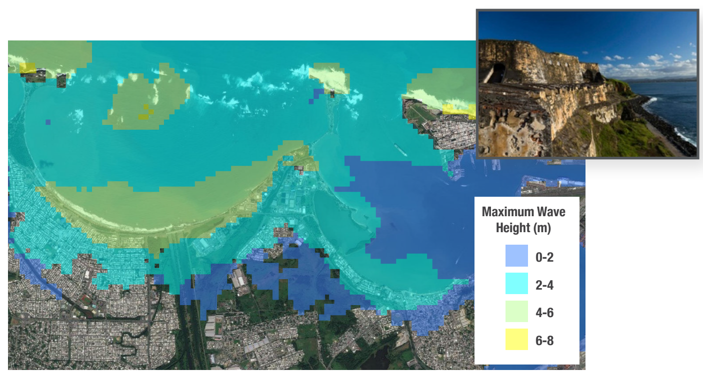
Current soil data reveal that many large population centers and ports in the Caribbean are underlain by loose, soft soil, making them susceptible to liquefaction; these ports include Kingston, Jamaica, and San Juan, Puerto Rico, which have 80% and 30% liquefaction susceptibility, respectively. According to these maps, one of the islands most at risk for liquefaction in the region is Jamaica, consistent with the historical observations of the 1692 M7.5 earthquake, which destroyed the man-made island of Port Royal.

In-house liquefaction susceptibility maps at 90-meter resolution were developed for each of the 29 countries modeled in the AIR Earthquake Model for the Caribbean. These data, along with groundwater maps and characteristic soil profiles, were used to determine potential liquefaction damage for a given level of ground shaking, providing explicit liquefaction coverage for the entire model domain.

A Probabilistic Tsunami Model for Caribbean Coasts

Nearly all Caribbean island nations have experienced tsunamis resulting from tectonic sources (both local and far-field), submarine landslides, and/or volcanic eruptions. The most recent destructive tsunamigenic earthquake to impact the Caribbean occurred in August 1946 just north of the Dominican Republic. Increases in coastal population and development in nearly all Caribbean nations, as well as an overall increase in tourism, have made coastal areas more vulnerable to tsunami risk. In addition, many of these coastlines are at low elevation and do not have any natural barriers to protect them.

The AIR model explicitly captures tsunami occurrence, intensity, and damage using a probabilistic approach. For each tsunamigenic earthquake in the catalog, the model captures the entire lifespan of the resulting tsunami—from the initial uplift of water to its onshore inundation. Loss due to tsunami is directly related to the difference between wave height and elevation, known as inundation depth. AIR's high-resolution Caribbean tsunami model captures details of the coastal landscape and elevation variations—which can differ substantially over short distances—at 90-meter resolution for more accurate risk assessment.



The coastal cliff of Castillo San Felipe del Morro, a citadel promontory sitting 140 feet above sea level in San Juan, Puerto Rico, remains dry in this modeled tsunami footprint caused by a simulated M8.3 earthquake in the Puerto Rico Trench, which demonstrates the importance of high-resolution elevation data in modeling tsunami risk.

The AIR model also captures the effect on properties of debris borne by tsunami waves. Tsunami-prone regions of the coast are characterized as zones of light, moderate, or heavy debris determined from satellite imagery. The resulting damage is a function of building construction type, occupancy, and height, as well as the tsunami's forward velocity and inundation depth.

Damage Functions Provide a Multi-Peril View of Vulnerability

The AIR Earthquake Model for the Caribbean features unique sets of peer-reviewed damage functions for modeling building, contents, business interruption, infrastructure, industrial facilities, and marine insurance losses resulting from ground shaking, liquefaction, and tsunami. These damage functions are based on spectral intensity to better represent the response of a structure to ground motion characteristics and explicitly capture the distinct aspects of each sub-peril to determine the vulnerability for a broad range of exposure types. Additional fidelity is built into the damage functions for building structures accounting for the evolution of building codes. In developing these damage functions, AIR partnered with local engineers and conducted a comprehensive evaluation of the evolution of building codes and local enforcement practices for each country within the model domain.

Other highlights of the vulnerability module include:

— Support for 125 construction and 110 occupancy classes, with four height bands and a country-specific number of age bands for each modeled country as well as unknown damage functions at the CRESTA level for instances when exposure information (e.g., construction type, occupancy, or height) is unavailable

— Vulnerability zonations based on seismic hazard and consideration for buildings designed to withstand wind damage (lateral forces), even if not constructed to an earthquake-specific building code

— Explicit support for large industrial facilities (e.g., pharmaceutical facilities, power plants, petrochemical plants, mines, and steel mills), infrastructure, marine cargo, marine hull, builder's risk, inland transit, and pleasure boats

The AIR Industry Exposure Databases for the Caribbean: An Unparalleled Resource

The AIR Industry Exposure Databases (IEDs) for the Caribbean consist of the latest available information on risk counts, building characteristics, and replacement costs, at a 90-meter resolution for each of the 29 countries within the model domain. Developed using local sources and on-the-ground observation, the IEDs capture the characteristics of properties at a high level of detail.

Footprints for each hotel, resort, and large industrial facility were developed, which capture the spread of buildings (e.g., a resort with separate buildings stretching along hundreds of feet of beachfront and extending back into non-waterfront areas), enabling the estimated value for each exposure to be realistically distributed across the entire site. Estimated values were developed from either capacity data (such as megawatts produced by a power plant or how much of a certain product a facility can produce) or other known features, such as building size.

A CONSISTENT VIEW OF EXPOSURES ACROSS THE REGION

The AIR Industry Exposure Databases for the Caribbean are used by both the AIR Earthquake Model for the Caribbean and the AIR Tropical Cyclone Model for the Caribbean, providing a consistent view of exposures across AIR models for the region.

Because data on earthquake damage are relatively scarce due to the infrequency of events, AIR conducts damage surveys to not only confirm modeling assumptions but also to improve understanding of the built environment's response to earthquakes. For example, damage surveys of Caribbean countries revealed the presence of mixed construction, where multiple construction types are present in one structure (e.g., a primarily concrete building with a wood-frame second story); these complexities are captured in the IEDs. Using satellite imagery facilitated the identification and location of large villas, which are often larger than average homes, have better construction, and have a higher rebuild cost.

The IEDs for the Caribbean also incorporate take-up rates by line of business at either the CRESTA or country level, depending on the country. In addition, the IEDs capture enhanced policy conditions and terms that reflect market conditions in the specific countries within the model domain, which can vary greatly from country to country in the Caribbean.

The benefits and uses of AIR's IEDs are numerous. They provide a foundation for all modeled industry loss estimates as well as being a critical part of model validation. Risk transfer solutions, such as industry loss warranties that pay out based on industry losses, rely on the IEDs. Using AIR's detailed modeling application, companies can also leverage the IEDs for the Caribbean to disaggregate the exposure data in their own portfolios to a highly detailed level for improved loss estimates.

AIR Damage Survey After the 2020 Puerto Rico Earthquake Confirmed and Enhanced View of Seismic Risk

Puerto Rico was struck by a series of quakes that began on December 28, 2019, and culminated in an Mw 6.4 mainshock on January 7, 2020. AIR engineers visited Ponce, Guánica, and Yauco to inspect structural damage from these quakes. The team's observations, together with the information gained from meetings with local engineers working on reconstruction, provided data that was leveraged during the development and validation of the AIR model. The AIR Earthquake Model for the Caribbean reflects these findings, incorporating the vulnerability of structures with the following mechanisms.

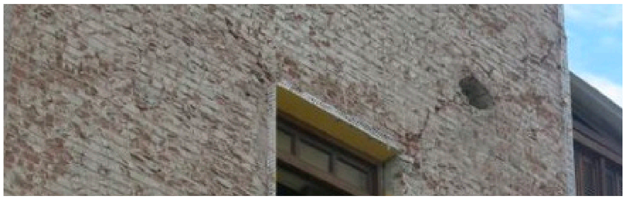
Short-column damage occurs when short columns—relatively short, stiff, brittle columns—attract large seismic forces, leading to severe damage and failure if they are not designed and/or reinforced appropriately.

Collapse of an elementary school in Guánica likely due to short-column failure.

Soft-story damage occurs when soft stories—levels in buildings that have noticeable stiffness/strength reduction in comparison to floors above or below—lead to collapse during an earthquake.

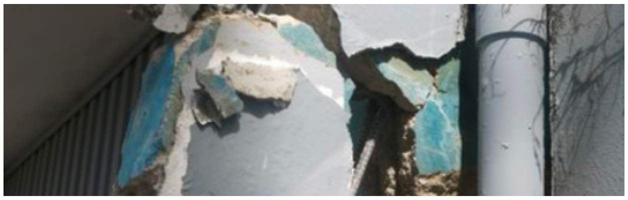
Soft story collapse of a mixed-use building in Guánica.

In-plane damage occurs when unreinforced, load-bearing masonry walls suffer shear failure (diagonal cracking), which generally start from corners of openings.



In-plane wall damage in Casa Sauri in Ponce.

Inadequate reinforcement damage occurs when a building lacks ductility—the ability to deform under stress—that could have been provided by detailed reinforcement in locations where structural failure potential is high.



Column failure due to inadequate reinforcement at a supermarket in Guánica.

A Comprehensive Approach to Model Validation

To ensure the most robust and scientifically rigorous view of risk, the AIR Earthquake Model for the Caribbean was built from the ground up, with each model component independently validated against scientific and historical data, as well as data from recent events. For example, ground motion prediction equations were validated using data recorded from recent earthquakes such as aftershocks following the 2010 M7.0 Haiti earthquake and the 2018 M7.3 earthquake that occurred north of Venezuela recorded in Trinidad and Tobago. Observations from historical data and geotechnical measurements (e.g., borehole data) were used to validate AIR's liquefaction susceptibility maps.

AIR also collaborated with academia. For example, AIR collaborated with the University of the West Indies and leveraged their proprietary soil measurements to validate soil maps for Trinidad and Tobago. Modeled losses show good agreement with historical observations

Model at a Glance

Modeled Perils	Shaking, liquefaction, and tsunami for 29 countries: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, BES Islands (special municipalities of the Netherlands—Bonaire, Sint Eustatius, and Saba), British Virgin Islands (BVI), Cayman Islands, Cuba, Curaçao, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Puerto Rico, Saint Barthelemy, Saint Kitts and Nevis, Saint Lucia, Sint Eustatius, Sint Maarten, Saint Martin, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, U.S. Virgin Islands (USVI)
Stochastic Catalog	All 29 countries share a time-dependent 10,000-year stochastic catalog; also available for analysis are 39 historical events and nine extreme disaster scenarios
Supported Construction and Occupancy Classes	125 construction and 110 occupancy classes, four height bands for all modeled perils, and country-specific age bands for each modeled country; supports damage to large industrial facilities, infrastructure, marine cargo, marine hull, builder's risk, inland transit, pleasure boats
Industry Exposure Databases	Each of the 29 Caribbean Industry Exposure Databases contains risk counts, building characteristics, construction costs, policy conditions, and take-up rates at 90-meter resolution

Model Highlights

— Explicitly models ground shaking, liquefaction, and tsunami across 29 Caribbean countries to capture the earthquake-triggered perils most responsible for insured loss in the Caribbean

— Captures the time-dependency of future earthquake events, accounting for the historical recurrence interval of earthquakes on known faults and the time since the last major rupture

— All 29 modeled countries share a 10,000-year stochastic catalog, facilitating modeling of portfolios that include multiple countries

— Includes complex, multi-fault earthquake rupture scenarios based on the most current data available

— Uses high-resolution soil maps to capture site amplification and liquefaction susceptibility

— Features a probabilistic high-resolution tsunami model that captures the propagation of a tsunami as well as details of the coastal landscape and elevation variations to determine potential inundation and damage of a given location

— Supports a variety of risk types, including large industrial facilities (e.g., pharmaceutical facilities, power plants, petrochemical plants, mines, and steel mills), infrastructure, marine cargo, builder's risk, and pleasure boats

— Features peer-reviewed peril-specific damage functions reflecting local building practices and the evolution of seismic codes

— Uses comprehensive, high-resolution Industry Exposure Databases that reflect the wide range of building characteristics across the region

ABOUT AIR WORLDWIDE

AIR Worldwide (AIR) provides risk modeling solutions that make individuals, businesses, and society more resilient to extreme events. In 1987, AIR Worldwide founded the catastrophe modeling industry and today models the risk from natural catastrophes, terrorism, pandemics, casualty catastrophes, and cyber incidents. Insurance, reinsurance, financial, corporate, and government clients rely on AIR's advanced science, software, and consulting services for catastrophe risk management, insurance-linked securities, longevity modeling, site-specific engineering analyses, and agricultural risk management. AIR Worldwide, a Verisk (Nasdaq:VRSK) business, is headquartered in Boston, with additional offices in North America, Europe, and Asia. For more information, please visit www.air-worldwide.com.

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