data for historic tsunamigenic events, including the relatively recent, 2010 Maule (Chile), and 2016 Kaikoura (New Zealand) earthquakes were used to validate the model. We create maximum inundation depth maps for several return periods, and discuss their implications for quantifying risk.

Simulation of PDC 2017 Asteroid Ocean Impact, Tsunami Generation, and Consequences on Japan's Coastlines

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Despite that the annual probability of an asteroid impact on earth is low, but over time, such catastrophic events are inevitable. Interest in assessing the tsunami generation and impact consequences has led us to develop a physics-based framework to seamlessly simulate the event from source (asteroid entry) to ocean impact (splash) to long wave generation, propagation, and inundation of the shoreline. The non-linear effects of the asteroid impact on the ocean surface are simulated using the hydrocode GEODYN to create the impact source for the shallow water wave propagation code, SWWP. The GEODYN-SWWP coupling is based on the structured adaptive mesh refinement infrastructure; SAMRAI developed at LLNL and has been used in FEMA table-top exercises conducted in 2013 through 2017, and the 2015 & 2017 Planetary Defense Conference exercise in Italy and Japan, respectively. We illustrate capabilities of this methodology by providing results of tsunami generation for different locations of asteroid impact off the East Coast of the United States, in the Gulf of Mexico, and near San Francisco. We present a comprehensive analysis of the PDC2017 asteroid impact on Japan's coastlines. Often the size of the asteroid is not deterministically known; thus, we explored the effect of asteroid size on the tsunami and landfall waves at several coastline cities of interest near the potential impact area. We construct the probability of wave height given the size of the asteroid and the location of the impact along the risk corridor. Such probability profiles can inform more sophisticated inundation models and advise emergency responses and disaster-mitigation efforts, and may be used for design of maritime protection (*e.g.* breakwaters walls) or assessment of risk to shoreline structures of interest (*e.g.* bridges, power plants). Finally, we compare asteroid-generated tsunamis to earthquake-generated tsunamis and the illustrate the impact of asteroids on climate change. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Field Survey of the 1946 Tsunami in the Dominican Republic Based on Eyewitness Interviews

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On 4 August 1946 an Mw 8.1 earthquake occurred off the north-eastern shore of Hispaniola resulting in a destructive tsunami with order one hundred fatalities in the Dominican Republic and observed runup in Puerto Rico. In the far field the tsunami was recorded on tide gauges on the US Atlantic Coast. The earthquake devastated the Dominican Republic and extended into Haiti. This was one of the strongest earthquakes ever reported in the Caribbean. The immediate earthquake reconnaissance surveys focused on earthquake damage and were conducted in September 1946 (Lynch and Bodle, 1948; Small, 1948). The 1946 Dominican Republic tsunami eyewitness based field survey took place in three phases from 18 to 21 March 2014, 1 to 3 September 2014 and 9 to 11 May 2016. The International Tsunami Survey Team (ITST) covered more than 400 km of coastline along the northern Dominican Republic from La Isabela to Punta Cana. The survey team documented tsunami runup, flow depth, inundation distances, coastal erosion and co-seismic land level changes based on eyewitnesses interviewed on site using established protocols. The early afternoon earthquake resulted in detailed survival stories with excellent eyewitness observations recounted almost 70 years later with lucidity. The Dominican Republic survey data includes 29 runup and tsunami height measurements at 21 locations. The tsunami impacts peaked with maximum tsunami heights exceeding 5m at a cluster of locations between Cabrera and El Limon. A maximum tsunami height of 8m likely associated with splash up was measured in Playa Boca Nueva. Tsunami inundation distances of 600m or more were measured at Las Terrenas and Playa Rincon on the Samana Peninsula. Some locations were surveyed twice in 2014 and 2016, which allowed to identify current coastal erosion rates. Field data points were corrected for predicted astronomical tide levels at the time of tsunami arrival in 1946. Individual tidal corrections applied to the raw field measurements were less than ±0.5m given the relatively small tidal range around Hispaniola Island. At least 10 significant tsunamis have been documented in the northern Caribbean since 1492, six of which are known to have resulted in loss of life (O'Loughlin and Lander, 2003). Rapid population increase in the Caribbean exposes more coastal residents and tourists to future tsunami events.

Tsunami Mitigation Mapping Effort in the Gulf of Mexico

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The devastating consequences of recent tsunami events in Indonesia (2004) and Japan (2011) have prompted a scientific response in assessing tsunami hazard even in regions where an apparent low risk or/and lack of complete historical tsunami record exists. Although a great uncertainty exists regarding the recurrence rate of large-scale tsunami events in the Gulf of Mexico (GOM) due to sparsity of data, geological and historical evidences indicate that the most likely tsunami hazard could come from a submarine landslide triggered by a moderate earthquake. Under these circumstances, the assessment of the tsunami hazard in the region is accomplished by means of using local ancient landslide information and also by using probabilistic approaches to identify more tsunami sources which are required to cover the entire GOM basin. By using 3D model for landslide source initial tsunami wave determination and 2D non-hydrostatic nested model for the propagation (15 to 5 to 3 arc-seconds) and inundation (1/3 arc-seconds), we are able to determine hazard to specific coastal locations, including maximum runup heights, inundation depth/extent, damaging currents and vorticity affecting communities and infrastructure, thus mitigating the impact of tsunamis according to mapping guidelines of the National Tsunami Hazard Mitigation Program.

Long-Lived Tsunami Edge Waves during the 2017 M 8.2 Tehuantepec, Mexico, Earthquake and Their Implications for Hazards

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Rare large normal faulting events can occur at subduction zones. Such is the case of the M8.2 Tehuantepec earthquake which ruptured away from the outer rise underneath the megathrust. The earthquake reactivated bend fault fabric and ruptured the entire lithosphere. Here we will discuss very long lived (48 hours) high amplitude tsunami edge waves observed at near source tide gauges during the event. We model the tsunami using a high resolution model of the earthquake source produced from all available regional geophysical observables. We find that the high amplitude and long duration of the edge waves is the result of the unique morphology of the Tehuantepec shelf. It is longer, and flatter than any continental shelf worldwide efficiently trapping the edge waves. The issue is important because edge-waves are a local site effect that compounds the tsunami hazard by amplifying the tsunami, delaying the highest wave arrival times, and extending the duration of high amplitude waves for many hours and potentially for days. Finally, we study the morphology of other continental shelves worldwide and identify hotspots where similar behavior will potentially be observed in future tsunamis.

Tsunami Threat Assessment for the North and Central Pacific Coast of Costa Rica

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Costa Rica has over 600 beaches, most of them populated. Tourism is a major economic activity of these coastal communities, present all year round due to tropical weather. There is a currently ongoing project to elaborate tsunami evacuation maps for the North and Central Pacific Coast of Costa Rica, funded by the National Emergency Commission (CNE). Twenty communities were chosen based on their tsunami risk. Tsunami vulnerability was defined by population and topographic conditions. To define the tsunami threat, the propagation of over 40 tsunamis was simulated numerically using ComMIT model over a 60 arcmin grid. The topography data was obtained from a LIDAR survey and the bathymetric data from nautical charts and global bathymetry. Sources were considered around the Pacific Basin, both in the near and far field. The resulting tsunami heights were superimposed to obtain a joint maximum tsunami height for each community. The highest joint tsunami heights were obtained for the southwestern coast of the Nicoya Peninsula and some isolated spots elsewhere. The amplification of the tsunami energy in those places was very likely due to the narrow continental platform and the effect of submarine landslide scars. The results can be employed to prioritize tsunami preparedness and warning efforts.

Pedestrian Evacuation Analysis in Case of Tsunami for the Puerto Rico Municipalities of Aguadilla, Arecibo and Ponce

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In the past decade, the world has witnessed of numerous tsunamis and earthquakes in different parts of the world such as Indonesia (2004), Peru (2007), Haiti and Chile (2010), Japan (2011) and the most recent one in Chile (2015) with waves close to 4.6 m and substantial damages. In Puerto Rico, the last tsunami that affected the island was in 1918, with waves greater than 5 m in height, causing damage and deaths, particularly in the western region, where first waves arrived in a matter of minutes. Pedestrian evacuation analysis permits evaluation of the travel time of an evacuation route taking into account different rates of pedestrian movement. According to data from the Puerto Rico Tsunami Ready program, more than 249,000 people reside within the tsuanami evacuation areas. It is important to know an estimate of the time of pedestrian evacuation of our exposed communities to demonstrate the danger of these and look for possible solutions to these cases. Here we present case study results of pedestrian analysis performed using Pedestrian Evacuation Analyst Tool in ArcGIS for three municipalities (counties) in Puerto Rico, Aguadilla, Arecibo, and Ponce. Based on these analysis, it is apparent that there are communities in Puerto Rico that their evacuation time is longer than the estimated arrival time of the tsunami. These regions require further consideration for additional mitigation including identifying alternate evacuation routes or identifying vertical evacuation sites. Results of the pedestrian analyses are publicly available through the Puerto Rico Tsunami Program Map Tool (TDST). This project provides valuable information for the emergency management officers and the residents to evaluate the risk and look for alternatives in order to lower the evacuation times of said exposed communities.

Urban Liquefaction and Lateral Spread Investigations and Mapping

Oral Session · Tuesday 15 May · 2:15 AM · Hibiscus A

Session Chairs: Gregory P. De Pascale and Jeffrey Bachhuber

Contemporary and Paleoliquefaction-Induced Lateral Spreading Mapping in Christchurch, New Zealand

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Earthquake triggered liquefaction and lateral spreading was widespread in Canterbury, New Zealand (NZ) during the 2010–2012 Canterbury Earthquake Sequence (CES) and led to ~$20 Billion NZD of damage. Although the causes and timing of liquefaction during the CES are well known, the geological controls on lateral spreading are more poorly- understood. We undertook a multi-disciplinary investigation funded by the National Science Foundation (NSF) and explored lateral spreading in Christchurch during the CES using image differencing displacement maps, field mapping, shear wave velocity profiles, boreholes and cone penetration (CPT) soundings, and paleoseismic trenching with radiocarbon dating. Preliminary results suggest that cumulative displacements from the CES are less than those observed in our trench along faults and index beds in the subsurface, and along a key down-dropped soil, when combined with clear paleoliquefaction at the site (*e.g.* faulted pre- CES sand boils) suggest at least one major pre-CES lateral spreading event here. The results of this mapping with aid us with mapping liquefaction and lateral spreading globally.

Lateral Spreading Analyses of the Existing Shoreline at Treasure Island

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Treasure Island is located in the central San Francisco Bay, immediately north of Yerba Buena Island, between the active San Andreas and Hayward faults. Treasure Island was constructed by placing hydraulic sand fill over natural shoal deposits within perimeter rock dikes. The natural shoal deposit consists of layers of clean sand, silty sand, and lenses of highly plastic clay. Full-scale and high-energy in-situ dynamic ground improvement test results indicated that, unlike the fill material, no appreciable ground improvement (*i.e.* densification) was observed within the shoal deposits. From a thorough geologic characterization of the shoal deposit and the results of laboratory cyclic direct simple shear tests on high-quality samples, it was concluded that the dynamic behavior of the natural shoal deposit could not be adequately captured by simplified conventional analytical methods, as the shoal deposit was found to be more resistant to seismically induced lateral deformation than could be predicted by simplified methods. Therefore, this study was undertaken to evaluate the seismic deformation of the existing shoreline at Treasure Island through a nonlinear dynamic deformation analysis. The scope of the study included seismic site response analyses, lateral deformation analyses using two-dimensional finite-element models in PLAXIS, pseudo-static hybrid deformation analyses, and comparisons with observed seismic performance of similar sites during past earthquakes. The shoal deposit was modeled using the UBC Sand model, with input parameters carefully selected to capture material behavior obtained through cyclic simple shear tests. Examination of PLAXIS analysis results indicates that the magnitude of lateral deformations at the location of the proposed development was negligible. A simplified method was also developed to be used as a screening tool for estimating the potential for lateral movement at other sites along the Treasure Island shoreline.

Urban Liquefaction Mapping for Water System Seismic Reliability, Portland, Oregon

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Conventional regional-scale urban liquefaction hazard analyses are typically performed using surficial geologic data, supplemented by representative but often limited subsurface data. These studies often do not fully capture the complicated subsurface stratigraphy critical to characterizing the distribution and thickness of strata potentially susceptible to liquefaction or associated lateral spreading that is damaging to distributed lifeline systems. Additionally, extrapolation for large magnitude earthquakes, such as an Mw = 9.0 Cascadia Subduction Zone earthquake, is often required. We performed a regional liquefaction hazard study for the Portland Water Bureau (PWB) using data from hundreds of borings across the Portland metro region to delineate three-dimensional (3D) subsurface conditions that could influence liquefaction and affect PWB's system. The database of geotechnical samples developed for this study provided representative soil parameters within specific geologic units. These data were linked with GIS-based 3D maps of the geologic units for the Portland metro region developed by the Oregon Department of Geology and Mineral Industries and with depth to groundwater developed by the USGS. Our database includes interpretation of each sample's liquefaction susceptibility, triggering potential, and post-triggering behavior for an array of seismic loading conditions, including a large Cascadia Subduction Zone earthquake. These data were combined in GIS and also analyzed to estimate median lateral spreading deformation. The liquefaction and lateral spread results were then incorporated into GIS, combining the detailed 3D subsurface geologic maps, groundwater maps, and seismic hazard maps to produce deformation maps that closely match site-specific analyses and provide quantitative estimates of liquefaction hazards for the entire urban water system.

Seismic and Liquefaction Hazard Maps for Lake County, Northwestern Tennessee

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