PRELIMINARY RESULTS OF THE U.S. NUCLEAR REGULATORY COMMISSION COLLABORATIVE RESEARCH PROGRAM TO ASSESS TSUNAMI HAZARD FOR NUCLEAR POWER PLANTS ON THE ATLANTIC AND GULF COASTS

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ABSTRACT :
In response to the 2004 Indian Ocean Tsunami, the United States Nuclear Regulatory Commission (US NRC) initiated a long-term research program to improve understanding of tsunami hazard levels for nuclear facilities in the United States. For this effort, the US NRC organized a collaborative research program with the United States Geological Survey (USGS) and other key researchers for the purpose of assessing tsunami hazard on the Atlantic and Gulf Coasts of the United States. The initial phase of this work consisted principally of collection, interpretation, and analysis of available offshore data and information. Necessarily, the US NRC research program includes both seismic- and landslide-based tsunamigenic sources in both the near and the far fields. The inclusion of tsunamigenic landslides, an important category of sources that impact tsunami hazard levels for the Atlantic and Gulf Coasts over the long time periods of interest to the US NRC, is a key difference between this program and most other tsunami hazard assessment programs. Although only a few years old, this program is already producing results that both support current US NRC activities and look toward the long-term goal of probabilistic tsunami hazard assessment. This paper provides a summary of results from several areas of current research. An overview of the broader US NRC research program is provided in a companion paper in this conference.

KEYWORDS:
Tsunami, Landslide, Seismic, Hazard, Nuclear

1. BACKGROUND

In response to the 2004 Indian Ocean Tsunami, as well as the anticipation of the submission of license applications for new nuclear facilities, the United States Nuclear Regulatory Commission (US NRC) initiated a long-term research program to improve understanding of tsunami hazard levels for nuclear power plants and other coastal facilities in the United States. To undertake this effort, the US NRC organized a collaborative research program with researchers at the United States Geological Survey (USGS), the National Oceanic and

Atmospheric Administration (NOAA), and other key researchers for the purpose of assessing tsunami hazard on the Atlantic and Gulf Coasts of the United States. The research described in this paper represents the combined effort of a diverse group of marine geologists, geophysicists, geotechnical engineers, and hydrodynamic modelers to evaluate tsunami sources that have the potential to impact the U.S. Atlantic and Gulf coasts.

The Atlantic and Gulf Coasts are the focus of this program, both because of the number of existing and proposed nuclear facilities located on these coasts and because many promising research efforts for assessing tsunami hazard in the Pacific Coast of the United States are already underway as a result of programs outside the US NRC. Tsunami has been long known as a hazard in the Pacific Ocean. However, the 2004 tsunami highlighted the fact the tsunamis can occur in other oceans that are less prepared for this rare phenomenon. Although tsunami are far rarer along the Atlantic and Gulf of Mexico coastlines, some areas can be highly vulnerable to tsunamis when they do occur because major population centers and industrial faculties are located near the shoreline at low-lying elevations, and often in estuaries. This is in comparison to the Pacific coast where tsunamis are more frequent but the coastline is more sparsely populated and most sections have more topographic relief.

Because the US NRC is interested in understanding hazard associated with the rare large tsunami that may occur over long time periods (in excess of 10,000 years), the research program was developed to investigate both seismic and landslide tsunamigenic sources. It also includes the study and characterization of large sources in the far field, as well as sources in the near field such that all key sources were considered. The study of near-field and far-field tsunamigenic landslides is a key difference between this research program and other tsunami hazard assessment programs, which are typically focused on seismic sources. Submarine landslides have also historically generated destructive tsunamis and so must be fully investigated in this program. In landslide initiated tsunami, the extent of damaging waves generated by landslides is generally smaller and more localized. However, along coastlines proximal to catastrophic submarine landslides, tsunami run-up can be significant as exemplified by the 1929 Grand Banks tsunami (Newfoundland and Nova Scotia), which likely had a significant landslide-generated component. Less is generally known about submarine landslides as tsunami triggers in comparison to their earthquake counterparts.

The development of tools and data to undertake probabilistic tsunami hazard assessments (PTHA) is a key long-term goal and the focus of later phases of the US NRC research program. Effectively developing PTHA tools will require an understanding of the frequency of different initiating events. Some areas in which the US NRC is likely to initiate additional work in the coming years relates to understanding the timing of the submarine landslides identified in the Atlantic. Some of the research discussed here represents the start of this long term element of the program.

Although less than two years old, this research program has already produced significant results that are currently or will soon be available to the public through a variety of technical publications. These publications include a USGS report to the US NRC (Ten Brink et al, 2007) and multiple articles in a special issue of Marine Geology to be published late 2008 or early 2009 (Barkana et al; Chaytor et al; Geist et al; Lee; Locat et al; Ten Brink et al, 2008). The early research and results discussed in the USGS report were focused on providing information on the source parameters useful for qualitative assessment of tsunami hazard for the Atlantic and Gulf coasts. The USGS report will be revised in 2008 and will include details related to the work summarized here. This information is currently being used to develop and review tsunami hazard assessments for new nuclear power facilities in the United States. A companion paper in this conference summarizes and discusses the complete US NRC program in more detail and provides a discussion of the seismic and landslide-based tsunami source characterizations (Kammerer et al, 2008).

2. SIZE DISTRIBUTION OF SUBMARINE LANDSLIDES ALONG THE U.S. ATLANTIC MARGIN AND ITS IMPLICATION TO TSUNAMI HAZARDS

The ability to determine the number, size, and frequency of large submarine landslides is a critical component in determining the hazard posed to coastal regions by destructive landslide-generated tsunamis. The efforts to characterize submarine landslides off the Atlantic coast represents the earliest effort of the US NRC tsunami research program. This work is investigating the size distribution of submarine landslides along the U.S. Atlantic continental slope and rise using the size of the landslide excavation regions. The data collected for this effort, a description of methods used, and other information is discussed in detail in the companion paper submitted to this conference (Kammerer et al, 2008).

The first step in the initial investigation of landslides in the Atlantic was the collection and analysis of a large amount of available information useful for the identification and characterization of offshore landslides along the Atlantic coast of the U.S. Multibeam bathymetry, Geologic Long-Range Inclined Asdic (GLORIA) sidescan sonar imagery, a regional grid of high-resolution seismic profiles, and published accounts of sediment cores from the region was collected. The near-complete coverage of the Atlantic continental slope and rise by multibeam bathymetry provided a key high-quality and uniform data set that allowed for a more detailed and consistent view and assessment of the geomorphology of submarine landslides than had been possible in the past.

This landslide mapping results indicated that landslides along the U.S. Atlantic margin initiate predominantly in two morphologic settings, canyon (heads and sidewalls) and on the open continental slope. The canyon-sourced failures often have several canyons feeding a single deposit, and the deposits are smaller than those derived from the open slope. As a result, they are unlikely to cause tsunami events. Open-slope failures commonly originate on the middle and lower slope in 800 to 2,200 m depths. These landslides extend farther offshore, are thicker, and have considerably larger volumes than their canyon derived counterparts. As a result of the large volumes of material that sometimes fail, open slope-sourced slides are considered to have the most potential to initiate tsunami. However, a significant volume of material may also be mobilized in landslides associated with areas of salt diapirism as well.

Landslide source excavation areas along the margin identified in a detailed bathymetric Digital Elevation Model (DEM) ranged between 0.89 km^2 and 2410 km^2. The volumes range between 0.002 km^3 and 179 km^3. The area to volume relationship of these source excavations is almost linear (i.e. the power law exponent is close to 1), suggesting a fairly uniform failure thickness of a few tens of meters in each event, with only rare, deep excavating landslides. The cumulative volume distribution of the excavations is well described by a log-normal distribution rather than by a power-law commonly used to describe both subaerial and submarine landslides. A log-normal distribution centered on a volume of 0.86 km3, may indicate that landslides preferentially mobilize a moderate amount of material (on the order of 1 km3), rather than large landslides or very small ones. Conversely, the log-normal distribution may reflect a power law distribution modified by a size-dependent probability of observing landslide excavations in the bathymetry data. If the latter is the case, for example, a power law distribution with an exponent of 1.3±0.3, modified by the conditional probability of success in identifying landslide excavations with increasing slide size, fits the observed size distribution equally well and predicts that geology of the source region has strong control on the size of the excavation. This exponent value corresponds favorably with the 1.2±0.3 predicted for subaerial landslides in unconsolidated material. The log-normal distribution of the observed excavation volumes suggests that large landslides, which have the greatest potential to generate damaging tsunamis, occur infrequently along the margin. The reader is directed to Chaytor et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

3. GEOLOGIC CONTROLS ON THE DISTRIBUTION OF SUBMARINE LANSLIDES ALONG THE U.S ATLANTIC CONTENTIAL MARGIN

Submarine landslides along the continental slope of the U.S. Atlantic margin are potential sources of tsunami hazard along the U.S. Atlantic coast. The magnitude of potential tsunamis depends on the volume and location of the landslides; and tsunami frequency depends on their recurrence interval. Unfortunately, both the size and recurrence interval of submarine landslides along the U.S. Atlantic margin is poorly understood.

Well-studied landslide-generated tsunamis in other parts of the world have been shown to generally be associated with earthquakes as a triggering mechanism. Because the size distribution and recurrence interval of earthquakes is generally better known than those for submarine landslides, if may be possible to estimate the size and recurrence interval of submarine landslides from the size and recurrence interval of earthquakes in the near vicinity of the potential landslides. To do this it is necessary to calculate the maximum expected landslide size for a given earthquake magnitude, use recurrence interval of each magnitude of earthquake to estimate the recurrence interval of landslides of a certain size, and assume a threshold landslide size that can generate a destructive tsunami.

The maximum expected landslide size for a given earthquake magnitude is calculated in 3 ways: by slope stability analysis for catastrophic slope failure on the Atlantic continental margin, by using land-based compilation of maximum observed distance from earthquake to liquefaction, and by using land-based compilation of maximum observed area of earthquake-induced landslides. We find that the calculated distances and failure areas from the slope stability analysis are similar or slightly smaller than the maximum triggering distances and failure areas in subaerial observations. The results from all three methods compare well with the slope failure observations of the Mw=7.2, 1929 Grand Banks earthquake, the only historical tsunamigenic earthquake along the North American Atlantic margin.

The results further suggest that a Mw=7.5 earthquake (the largest expected earthquake in the eastern U.S.) must be located offshore and within 100 km of the continental slope to induce a catastrophic slope failure. Thus, based on this method a repeat of the 1755 Cape Anne and 1881 Charleston earthquakes would not be expected to cause landslides on the continental slope. The observed rate of seismicity offshore the U.S. Atlantic coast is very low with the exception of New England, where some seismicity is observed. An extrapolation of annual strain rates from the Canadian Atlantic continental margin suggests that the New England margin may experience the equivalent of a magnitude 7 earthquake on average every 600 to 3000 years. A minimum triggering earthquake magnitude of 5.5 is suggested for a sufficiently large submarine failure to generate a devastating tsunami only if the epicenter is located within the continental slope. The reader is directed to Twitchell et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

4. GEOMORPHOLOGY, STABILITY, AND MOBILITY FROM THE CURRITUCK LANDSLIDE

In order to gain an initial understanding of the implications of the mapped landslides on the tsunami hazard along the Atlantic coast, a study to characterize and perform hydrodynamic modeling of the Carrituck landslide was undertaken. Tsunami magnitude depends strongly upon the size of the slide and how the landslide moves as it fails and flows. Therefore, the first step in the process was to determine the parameters needed for the tsunami generation and propagation modeling. This work had significant challenges because the initial geometry of the material was not known, it was unclear if there had been a single event or multiple events, and the properties of the geologic material were not well characterized. During this work several issues were considered and the researchers endeavored to answer the following multiple lines of inquiry. Ultimately a possible initial velocity and acceleration of the failed mass was developed from the mobility analyses.

The Currituck slide, located off the coast of Virginia, is a major submarine mass movement that was likely triggered during a time of low sea level. This slide removed a total volume of about 165 km^3 from this section of the continental slope. The departure zone still shows a very clean surface that dips at 4° and is only covered by a thin veneer of Holocene sediment. Multibeam bathymetric data suggest that this slide took place along three failures surfaces. The morphology of the source area suggests that the sediments were already at least normally consolidated at the time of failure. The slide debris covers an area as much as 55 km wide that extends 180 km from the estimated toe of the original slope.

The back analysis of slide initiation indicates that very high pore pressure, a strong earthquake, or both had to be generated to trigger slides on such a low failure plane angle. The shape of the failure plane, the fact that the surface is almost clear of any debris, and the mobility analysis, all support the argument that the slides took place nearly simultaneously. Potential causes for the generation of high pore pressures could be seepage forces from coastal aquifers, delta construction and related pore pressure generation due to the local sediment loading, gas hydrates, and earthquakes.

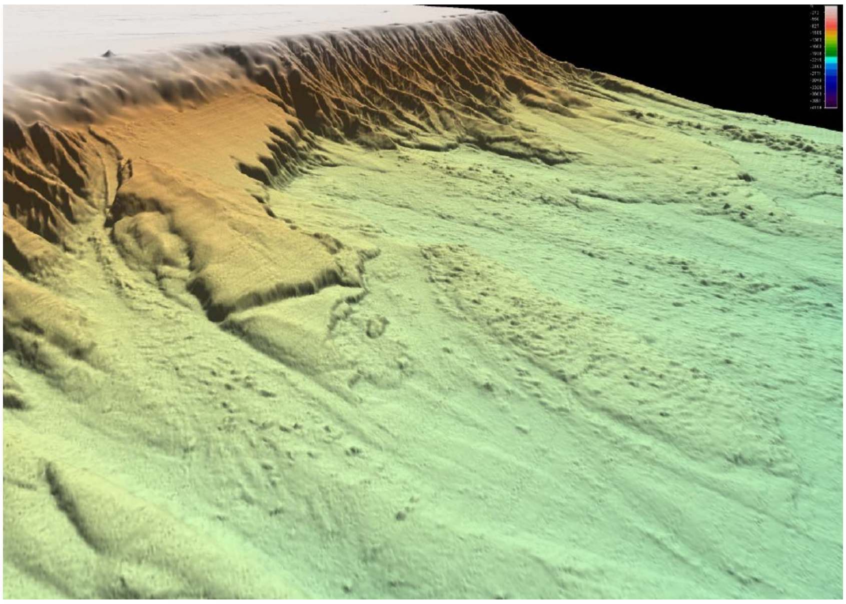

Figure 1 Image of the Currituck Landslide Off the U.S. Atlantic Coast

This slide, and its origin, is a spectacular example of the potential threat that submarine mass movements can pose to the US Atlantic coast and underline the need to further assess the potential for the generation of such large slides, like the Grand Banks 1927 landslide of similar volume. The reader is directed to Locat et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

5. HYDRODYNAMIC MODELING OF TSUNAMIS FROM THE CURRITUCK LANDSLIDE

Once estimates of the important landslide parameters of the Currituck landslide offshore North Carolina had been developed in the research discussed above, preliminary hydrodynamic modeling of the slide was conducted for the purpose of determining the range of possible near-shore wave heights and understanding the possible impact of the continental shelf. A long and intermediate wave modeling package (COULWAVE) based on the non-linear Boussinesq equations was used to simulate the tsunami. This model includes procedures to incorporate bottom friction, wave breaking, and overland flow during run-up. Potential tsunamis generated from the Currituck landslide were analyzed using four approaches: (1) the tsunami wave history was calculated from several different scenarios indicated by geotechnical stability and mobility analyses; (2) a sensitivity analysis was conducted to determine the effects of both landslide failure duration during generation and bottom friction along the continental shelf during propagation; (3) the wave history was calculated over a regional area to determine the propagation of energy oblique to the slide axis; and (4) a high resolution 1D model was developed to accurately model wave breaking and the combined influence of nonlinearity and dispersion during near-shore propagation and run-up.

From the sensitivity analyses, it was concluded that the primary source parameter that affected tsunami severity for this case study is landslide volume, with failure duration having a secondary influence. Bottom friction during propagation across the continental shelf also has a strong influence spectrum on the attenuation of the tsunami during propagation. The high-resolution1-D model also indicates that the tsunami undergoes non-linear fission prior to wave breaking, generating independent, short-period waves. Wave breaking occurs approximately 40 to 50 km offshore, where a tsunami bore is formed that persists during run-up. These analyses illustrate the complex nature of landslide tsunamis, necessitating the use of detailed landslide stability/mobility models and higher-order hydrodynamic models to determine their hazard.

This study was undertaken early in the program and played an important role for the US NRC because the modeling allowed staff to understand the general implications of the initial landslide mapping results. It also helped to scope and focus the organization of the broader research program. The reader is directed to Geist et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

6. ASSESSMENT OF SOURCE PROBABILITIES FOR POTENTIAL TSUNAMI AFFECTING THE U.S. COASTS

A key element of determining overall risk to a coastal facility from tsunami is understanding the likelihood that a tsunami will occur. Estimating the likelihood of tsunamis occurring along the U.S. Atlantic coast critically depends on knowledge of the annual probability of all potential tsunami sources that may impact a site of interest. To address this need a review of available information on both earthquake and landslide probabilities from potential sources that could generate local and transoceanic tsunamis was performed. Estimating source probability includes defining both size and recurrence distributions for earthquakes and landslides. For the former distribution, source sizes are often distributed according to a truncated or tapered power-law relationship. For the latter distribution, sources are often assumed to occur in time according to a Poisson process, simplifying the way tsunami probabilities from individual sources can be aggregated. For the U.S. Atlantic coast, earthquake tsunami sources primarily occur at transoceanic distances along plate boundary faults. Probabilities for these seismic sources can be constrained from previous statistical studies of recorded seismicity.

In contrast, there is presently little information constraining landslide probabilities that may generate local tsunamis. Though there is significant uncertainty in tsunami source probabilities for the Atlantic, results from this study have yielded a comparative analysis of tsunami source recurrence rates that can form the basis for future probabilistic analyses. The reader is directed to Geist et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

7. TIMING OF LARGE SUBMARINE LANDSLIDES ON THE ATLANTIC OCEAN MARGIN

The frequency of occurrence of tsunami due to specific sources, such as tsunamigenic landslide is a necessary and important parameter required for any probabilistic tsunami hazard assessment (PTHA). Thus, developing and understanding of the frequency of tsunamigenic landslides that may impact the U.S. coastline is an important element in reaching the long term program goal of developing PSHA tools for the Atlantic and Gulf coasts.

However, landslides are complicated and non-stationary process. Submarine landslides are distributed unevenly both in space and time. Spatially, they occur most commonly in fjords, active river deltas, submarine canyon-fan systems, the open continental slope, and on the flanks of oceanic volcanic islands. Temporally, they are influenced by the size, location, and sedimentology of migrating depocenters, changes in seafloor pressures and temperatures, variations in seismicity and volcanic activity, and changes in groundwater flow conditions.

In the past, the dominant factor influencing the times of submarine landslide occurrence has been glaciation. A review of known ages of submarine landslides along the margins of the Atlantic Ocean, augmented by a few ages from other submarine locations shows a relatively even distribution of large landslides with time from the last glacial maximum until about five thousand years after the end of glaciation. During the past 5000 years the frequency of occurrence is less by a factor of 1.7 to 3.5 than during or shortly after the last glacial/deglaciation period. Such an association likely exists because of the formation of thick deposits of sediment on the upper continental slope during glacial periods and increased seismicity caused by isostatic readjustment during and following deglaciation. Hydrate dissociation may play a role, as suggested previously in the literature, but the connection is unclear.

Developing a full understanding of the rate of past event, as well as the underlying causes, will continue to be an important research topic within the US NRC program. By understanding the underlying causes of past behavior, a more informed assessment of future rates will be possible. The reader is directed to Lee (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

8. INVESTIGATION OF THE SOURCE OF THE 1755 LISBON EARTHQUAKE AND TSUNAMI USING TRANS-OCEANIC MODELING

Four large tsunamigenic earthquakes have occurred in the Atlantic Ocean west of Gibraltar in the last 300 years. The great Lisbon earthquake is one of these. However, there is no simple tectonic model for this area that explains the generation of these earthquakes. As a result, promising work undertaken to determine the source parameters of the 1755 Lisbon earthquake is of particular interest.

The Lisbon earthquake occurred in 1755 and had an estimated moment magnitude of 8.5 to 9.0. It was the most destructive earthquake in European history. In the near field associated tsunami run-up was reported to have reached 5-15 m along the Portuguese and Moroccan coasts and the run-up was significant at the Azores and Madeira Island. Lander et al. (2002) compiled a list of reports on the effect of the 1755 Lisbon tsunami in distant locations such as the Caribbean: Antigua, Saba, St. Martin at the northeast corner of the Caribbean had the highest flooding, flooding was also reported from Santiago de Cuba and Samana Bay, Dominican Republic, in the north to Barbados in the south. There are also reports about flooding in Bonavista, north of St. Johns, Newfoundland. However, there are no reports of flooding anywhere else between Cuba and Newfoundland, despite the presence at that time of population centers in low-lying areas of the eastern U.S. and Canada.

A variety of past studies have hypothesized various sources for this earthquake based on geophysical surveys, modeling the near-field earthquake intensity, or tsunami effects. However, as part of this research, modeling of various sources is being undertaken to determine the source location and geometry that best fits the many far field records of tsunami impacts from the earthquake. Prior to this project there had not been an attempt to fit cross-ocean tsunami reports of the 1755 Lisbon earthquake to any of the proposed fault sources. Studying far field effects, as undertaken in this research, is advantageous because the tsunami is less influenced by near source bathymetry and is unaffected by triggered submarine landslides at the source. Source location, fault orientation and bathymetry are the main elements governing transatlantic tsunami propagation to sites along the U.S. East Coast, much more than distance from the source and continental shelf width.

Results of the far and near-field tsunami simulations undertaken and a relative amplitude comparison limit the earthquake source area to a region located south of the Gorringe Bank in the center of the Horseshoe Plain. This is in contrast with previously suggested sources such as Marqués de Pombal Fault, and Gulf of Cádiz Fault, which are farther east of the Horseshoe Plain. The earthquake was likely to be a thrust event on a fault striking ~345° and dipping to the ENE as opposed to the suggested earthquake source of the Gorringe Bank Fault, which trends NE-SW. Gorringe Bank, the Madeira-Tore Rise (MTR), and the Azores appear to have acted as topographic scatters for tsunami energy, shielding most of the U.S. Atlantic Coast from the 1755 Lisbon tsunami. Additional simulations to assess tsunami hazard to the U.S. Atlantic Coast from possible future earthquakes along the Azores-Iberia plate boundary indicate that sources west of the MTR and in the Gulf of Cadiz may affect the southeastern coast of the U.S. The Azores-Iberia plate boundary west of the MTR is characterized by strike-slip faults, not thrusts, but the Gulf of Cadiz may have thrust faults. Southern Florida seems to be at risk from sources located east of MTR and South of the Gorringe Bank, but it is mostly shielded by the Bahamas. The Gulf of Cádiz is another source area of potential tsunami hazard to the U.S. Atlantic Coast. Higher resolution near-shore bathymetry along the U.S. Atlantic Coast and the Caribbean as well as a detailed study of potential tsunami sources in the central west part of the Horseshoe Plain are necessary to verify the simulation results. The reader is directed to Barkana et al (2008) or the 2008 revision of the USGS report to the US NRC (Ten Brink et al, 2008) for additional details.

9. SUMMARY

This paper highlights some recent results from research performed for the US NRC tsunami research program. This information is provided as an overview of the types of projects undertaken in the program. The goal of the program is to develop an understanding of the deterministic hazard from tsunami along the U.S. Atlantic and Gulf coasts in the short term, with a long-term goal of developing the tools and parameters necessary to perform probabilistic seismic hazard assessments. The research here represents a wide variety of topics that are essential to ultimately meet these goals. For additional information, please see the companion paper in this conference (Kammerer et al, 2008).

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