NTHMP Project FY 2012 -2013

Project Name/Title:	**A probabilistic methodology for hazard assessment of tsunami generated by subsea landslide and for construction of tsunami inundation maps in the Gulf of Mexico**
Project Dates:	August /2012 to July /2014
Recipient Institution:	Texas A&M University at Galveston
Primary Contact:	Dr. Juan J. Horrillo
Primary Contact Address:	Physical Address: Seawolf Parkway Galveston, TX 77554 Mailing Address: P.O. Box 1675 Galveston, TX 77553
Telephone Number:	(409)740-4465
Fax Number:	(409)741-7153
Primary Contract Email:	horrillj@tamug.edu
Project Website:	http://www.tamug.edu/mase/BiographyPages/Horrillo.htm

Executive Summary

A probabilistic methodology for hazard assessment of tsunami generated by subsea landslide and for construction of tsunami inundation maps in the Gulf of Mexico

Submitted to the National Tsunami Hazard Mitigation Program (NTHMP) Modeling and Mapping Subcommittee by: Juan J. Horrillo, John Sweetman, Arash Zakeri and Charles Williams

Motivation

NTHMP Performance Metrics:

1- "support a research effort to develop U.S. tsunami hazard assessment methodologies".
2- "develop quantitative tsunami hazard analysis techniques including source determination and probability of occurrence".

Goal

Develop a methodology for tsunami hazard assessment with application at a specific GOM's region that combines probabilistic submarine landslide hazard analysis with simplified/efficient deterministic techniques for sediment slope stability and tsunami generation, propagation and runup.

Deliverables

1- Report documenting the submarine landslide tsunami hazard analysis tools.
2-Application of the hazard analysis tools to the GOM's northwestern region (South Padre Island -Galveston, TX.).
3- GOM's sediment/soil parameters (geo-dataset) assimilated from publically available information and determined from laboratory testing in form of a database for slope stability and debris flow analyses and ultimately, tsunami modeling.
4- Probabilistic tsunami runup model output data and products
5- Simplified 2D sediment/soil slope stability analysis and debris flow model
6- Fast-optimized 2D shallow water numerical code for wave propagation and runup.
7- Site-specific, map-based hazard assessments with the greatest flood hazard
8- Site-specific 100, 500 and 10000 years annual exceedance values (runup height)
9- locations and characterization of most likely tsunami scenarios (tsunami sources) associated to potential landslide events with probability of recurrences
10- At least two publications in recognized journal papers in joint probabilities

Proposed Study Areas

GOM's northwestern region (From South Padre Island to Galveston, TX., including the Matagorda County Nuclear Plant)

Timeline

August /2012 to July/2014

Budget

US$498,630.00

Proposal

A probabilistic methodology for hazard assessment of tsunami generated by subsea landslide for construction of tsunami inundation maps in the Gulf of Mexico

Submitted to the National Tsunami Hazard Mitigation Program (NTHMP) Modeling and Mapping Subcommittee by
Juan J. Horrillo, John Sweetman, Arash Zakeri and and Charles Williams.

Goal

The objective this project is to assess the tsunami hazards generated by submarine landslides that may impact coastal communities and infrastructure in the Gulf of Mexico (GOM). The project aims to develop a methodology for tsunami hazard assessment that combine probabilistic submarine landslide analysis with a deterministic estimate of: a) sediment slope stability; b) wave propagation and runup.

The nondeterministic assessment is based on a large number of Monte Carlo simulations in which distributions of certain parameters (seismicity acceleration, sediment mechanic properties, landslide type, landslide volume or area, failure location and water depth, etc.) are used to carry out simplified slope stability analyses for the generation of extreme values of the initial tsunami wave configuration. Site-specific analysis with a lesser number of tsunami calculations will be performed using a fast-optimized 2D shallow water numerical model (that has been thoroughly documented and validated) to establish probabilistic extreme values for runup height in the Northwest of GOM. The methodology will be supported with a parametric statistical study that will be applied a priory to determine which specific physical parameters are important in the generation of extreme values of the initial tsunami wave configuration and thus diminishing the number of possible combinations. The study will be carried out by a qualified team of research professionals with a proven track record on probabilistic hazard assessments, tsunami hydrodynamics, and underwater sediment slope stability modeling. The final product will yield site-specific map-based tsunami hazard assessments that benefit urban planners and emergency managers. Results of this study will play a role in advancing our understanding of landslide tsunamis, and thus contribute to building a safer GOM coastal community.

Motivation

The strategic plan of the NTHMP program recommends that over the next 5 years program resources be weighted appropriately between activities that improve the level of community preparedness and the state of tsunami science. The NTHMP Performance Measures and Milestones include a strategy to *"support a research effort to develop U.S. tsunami hazard assessment methodologies"* in order to *"develop quantitative tsunami hazard analysis techniques including source determination and probability of occurrence"*.

Background

Gulf of Mexico coasts have been included to the U.S. Tsunami Warning System since January 2005. The main purpose of the warning system is to enable local emergency management to act in response to warnings. To plan for the warning response, emergency managers must understand what specific areas within their jurisdictions are threatened by tsunamis.

Potential tsunami sources for the GOM are local submarine landslides and earthquakes (induced co-seismic tsunami source) along the Caribbean plate boundary faults. However, preliminary modeling of potential tsunami sources outside the GOM by Knight, (2006) indicated a very low threat and may not pose a tsunami hazard to the GOM coastal communities or infrastructure. Nevertheless, ancient submarine landslides within the GOM may have generated tsunamis in the past, as examined by the Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group (THAG), ten Brink et.al., 2009. In their findings, they state that submarine landslides in the GOM are considered a potential tsunami hazard for the following reasons: 1. Some dated submarine landslides in the GOM have a post-glacial age; 2. Large landslides in the GOM have been found in the submarine canyons and fan provinces extending from present Mississippi and other former large rivers that emptied into the GOM. These large submarine landslides were probably active before 7,500 years ago; 3. Recent suggestions from seismic records of small-scale energetic submarine landslides in the GOM indicate that there is a probability of recurrence.

Hazard areas can be determined by historical events, by modeling potential tsunami events (worst case scenario), or by using a probabilistic approach. As the GOM has no significant recent historic tsunamis records, addition of a probabilistic component to the existing numerical modeling capability will enable a realistic assessment of coastal hazard zones. The proposed method is to determine the likelihood of tsunami events by combining critical physical parameters to develop probability distributions of the magnitude of the initial tsunami and predicting the probabilistic tsunami hazard at specific locations along the shoreline. Several efforts in recent years on the topic are palpable and will contribute to this effort; for instance: Maretzki, Grilli and Baxter, 2007, presented results of a probabilistic analysis that estimates the hazard expressed in terms of runup at a given probability of occurrence of the slide mass failure tsunamis triggered by earthquakes, on the upper northeast coast of the United States. They employed a large number of Monte Carlo Simulation (MCS), in which distributions of relevant parameters (seismicity, sediment properties, slide type, location of slide, volume of slide, water depth, etc.) were used to perform large numbers of stochastic stability analyses of underwater slopes, based on standard geotechnical methods. Later, Gonzalez*, et.al.*, 2009 generated the first probabilistic tsunami flooding maps by using integrated tsunami propagation modeling with methods of probabilistic seismic hazard assessments with application to Seaside, Oregon, which yielded estimates of the spatial distribution of 100 and 500 years maximum tsunami amplitudes. The method quantified estimates of the likelihood and severity of the tsunami hazard, which could then be combined with vulnerability and exposure to yield estimates of tsunami risk.

The proposed methodology shares several aspects of the cited works. Yet, it is envisaged to assess the tsunami hazards by means of a more complete and efficient methodology where the large number of MCS for the distribution of relevant parameters to obtain the tsunami initial source from the sediment-slope stability analysis will be combined with a lesser number of tsunami propagation model predictions inferred from a parametric statistical in which most important physical parameters are indentified for extreme values of tsunami initiation. The probabilistic methodology will alternate with deterministic estimate of: a) sediment-slope stability using Limit Equilibrium Methods; b) wave propagation and runup by means of optimized 2D and efficient hydrodynamic numerical model. A site-specific, map-based hazard assessments with the greatest flood for 100, 500 and 10000 year annual exceedance values and locations associated to potential underwater landslide events with probability of recurrences will be obtained along the Northwestern part of the GOM.

Approach

The basics of this multidisciplinary study is to adapt several independent tools to quantify the hazard potentially caused by large submarine landslide events in the GOM, and will build upon probabilistic, geotechnical engineering, marine geology and wave hydrodynamic science methods. The work will focus on tsunami-related-hazards triggered by earthquakes.
The proposed methodology will be executed through the combination of the following tools:

A) Probabilistic Hazard Assessment Model:

There are three main tasks in the probabilistic portion of the proposed work. 1) A probabilistic tsunami hazard assessment based on a large number of Monte Carlo Simulations (MCS's) of tsunami initiation events combined with a lesser number of tsunami propagation model predictions, 2) a parametric statistical study to determine which specific physical parameters are most important to definition of extreme values of tsunami initiation events, and 3) analytical combination of the random variables representing the physical parameters using random variable algebra. This may enable precise preservation of all randomness despite a reduction in the required number of MCS simulations.

1) Probabilistic Tsunami Hazard Assessment:

The tsunami-landslide problem is sufficiently complex that it is difficult to develop simple analytical probability models for the process; application of empirical probability models to predict extreme events generally requires more historical data of very large tsunami events than is typically available, and that data should ideally include accurate estimates of inter-event times, which are also not commonly available. Subsequently, various researchers have opted for use of MCS to predict landslide and subsequent tsunami events. There are three main challenges with MCS: 1) Determining the likelihood of tsunami causing events, 2) computationally combining those events to develop probability distributions of the magnitude of initial tsunami waves at individual locations, 3) combining the probabilities of tsunami initiation to predict the probabilistic tsunami hazard at specific locations along the shoreline, and 4) combining the joint-probability effects associated with one earthquake triggering multiple landslides.

The simulation work proposed here will make use of the concept underlying the commonly-used Probabilistic Seismic Hazard Analysis (PSHA) originally developed by Allin Cornell in 1968 (Cornell, 1968), and modified for use as Probabilistic Tsunami Hazard Analysis (PTHA) by Lin and Tung, 1982. The general equation for aggregating the hazard probabilities to compute the expected rate of tsunamis with runup greater than R_0:

$$\lambda(R>R_0) = \sum_i v_i \iint P(R>R_0 \mid \Psi_i, r) f(\Psi_i) f(R|\Psi_i)\, dr\, d\Psi_i \quad (1)$$

Where the finite sum is taken over all i source types; v_i is the mean rate for each source type, and $P(R>R_0 \mid \Psi_i, r)$ is the conditional probability of runup exceeding R_0, given the distance r and the source parameters Ψ_i. In general, MCS to determine extreme fractiles requires an extremely large numbers of random simulations, because for complex processes like tsunami generation that rely on combinations of many random variables, the most extreme events result from random combinations of rare extreme values of the underlying variables. These underlying values are physical parameters such as seismic activities, precise proximity of seismic activity

and the potential slide failure, local soil properties, slope steepness, slope stabilities and so forth. Each important physical parameter must be treated as a random variable described by a mean, standard deviation, and a distribution shape. The large number of these random variables leads to needing a very large number of simulations in the MCS to reasonable define the tail of the tsunami initiation distribution. Millions of simulations would be required to obtain a reasonable tail distribution for tsunami initiation. It would be impractical, for computational reasons alone, to execute millions of runs of a tsunami propagation model.

To resolve this computational issue, the work proposed here is to treat the distance *r,* not as a random variable for the tsunami propagation computation, but as a discrete and specific value, representative of a physical region in the GOM, and then summing probabilities in equation (1) over all *r* to represent all hazardous regions of the GOM. This representation enables treatment of the quantity $P(R>R_0 \mid \Psi_i)$ in equation (1) as a deterministic quantity: $P(R=R_0 \mid \Psi_i) = 1$, i.e., it is assumed that given an initial surface depression at a known location, the size of the runup due to that event is a deterministic quantity. This reasonably modest assumption dramatically reduces the number of required tsunami propagation simulations. In this procedure, a very large number of MCS simulations (e.g. 10^6) will be used to determine a full probability distribution of the ocean wave depression depth at a specific site, complete with a computed uncertainty at each fractile. With that cumulative distribution defined, a very limited number of pre-specified fractiles (e.g.10^1) will be used to compute the runup at several coastal locations (e.g. 10^2). The depression depth associated with each of the pre-specified fractiles is well-defined because it is based on a very large number of simulations. The deterministic tsunami propagation model is then used with each sea surface depression to predict the runup at each shore location from each tsunami initiation event at each of the *i* source types at each initiation site. The final step is to probabilistically combine the all of the pre-defined discrete locations in the GOM that are capable of initiating a tsunami. Joint occurrences of landslides will be addressed without need for additional deterministic simulations by summing the independently computed time series for single landslide events at nearshore grid locations. The result of the simulation study is a hazard curve (probability of exceedence of specific runup heights), and an associated variance for each fractile.

2) Parametric Statistical Study:

The overall goal of this task is to assess the relative importance of specific physical parameters in the prediction of tsunami hazard. Many of the physical parameters that need to be quantified for accurate assessment of tsunami hazard are poorly known; the goal here is to statistically determine how much more accurately the tsunami characteristic could be predicted if additional physical data was collected, and to determine which additional physical data would be most valuable. In general, there are two sources of uncertainty in statistical representations of physical data: aleatory uncertainty results from variabilities of the physical quantity inherent in nature, and epistemic uncertainties result from lack of knowledge. Epistemic uncertainties can generally be reduced by collecting more data. The approach to this task will be purely numerical-simulation based: the variance of a single physical parameter leading to tsunami initiation (i.e., density of sediment) will be reduced and the MCS simulation for selected locations from Task 1 will be repeated. The computed uncertainly at each fractile of the surface depression wave depth will be compared with equivalent results of Task 1: those physical

parameters leading to the greatest reduction in uncertainty would be the most valuable data for collection in future ocean surveys.

3) Analytical Combination of the Random Variables:

This task is to apply analytical computations to combine the various random variables used as input to the simplified tsunami initiation model used to predict the size of the initial wave depression. This model must be reasonably simple for the very large number of MCS simulations to be computationally manageable. The predictive model uses random variables to represent the physical parameters leading to tsunami generation: in the MCS simulations, a single value of each of these random variables is drawn from a distribution and the resulting initial depression is computed. Here, the random variables are to be analytically combined as far as possible while still maintaining the variance and distribution type of each variable, the goal is to condense the number of variables such that fewer random inputs must be used in each simulation. This condensation has the potential to significantly reduce the number of required MCS simulations. Analytical work also has the clear benefit that results can be effectively used by future investigators to potentially reduce the number of simulations required for PTHA computations at other geographic locations.

B) Sediment-Slope stability Model

The main goal of this task is to provide the input parameters needed for the MCS's and later for hydrodynamic modeling to estimate the set-down or initial surface depression. Random sampling from the distributions of the slope and soil parameters will be used in a large number of Monte Carlo simulations to assess the probabilities of various slope stability failures for each of the target locations (approximately 40) on the Northwestern continental shelf of the Gulf of Mexico. Three parameters will be assessed for each predicted slope stability failure: volume of moving soil, acceleration of that volume and water depth of the center of the sliding mass. The final output of the slope stability model will be statistical distributions of each of the three parameters most critical for the hydrodynamic model to predict the initial depression of the free surface, including any correlations found to be important.

Most common causes are submarine landslides are earthquakes, storm wave loading, sedimentation, tidal changes and gas seepage from subsurface reservoirs. Earthquakes (e.g. USGS, 2011a, ten Brinks, 2009) and wave induced landslides have occurred in the past (e.g. Hurricane Camille in 1969, Bea and Aurora, 1982). The structural geology in GOM is complex and contains a dense population of faults. Further, the lateral salt movement and salt ascension of the salt bodies in GOM have also the potential for causing slope instability. However, to quantify hazards from these causes in a probabilistic manner associated it would be impractical not only to attempt to concurrently consider all slope failure mechanisms, but also to perform direct numerical simulations for the large number of potential scenarios required for a proper hazard assessment. Therefore, a simple, but practical, approach is proposed. The slopes on the shelf and Western Slope up to water depth about 1,500 m within the study area will be considered. The slopes will be screened and categorized in terms of steepness based on the actual publically available bathymetric maps. The potential of the aforementioned natural causes on slope instability will be considered. Seismicity will be determined from the seismic hazard maps (USGS, 2011b), and regional geology, salt body movement and sediment rating will be

obtained from publically available sources. Candidate slopes will be selected for slope stability analysis.

Establishing the right soil model and parameters remains a critical constituent to evaluating the slope stability and the hazards associated with submarine landslides. Given the exploration and development activities in GOM, a significant amount of data has been collected; however, some of this information is proprietary, and other available data is a from various sources. A secondary goal of this task is to develop a geo-dataset consisting of soil parameters at a high-level and make available to tsunami researchers for future uses or posterior investigation in the GOM. For slope stability modeling, publically available datasets (geotechnical and geophysical) and experience in the region will be used to create seabed models (stratigraphy, settings, anomalies, etc.) and establish the soil parameters required.

Seabed sediments in the study area are expected to mainly be cohesive (clayey) in nature. However, there may be a possibility for discontinuous and/or occasional cohesionless (sandy) layers. 2D Limit Equilibrium methods (e.g. simplified Bishop, Morgenstern-Price, infinite slope, etc.) will be used for slope stability analysis capturing failure types ranging from rotational to translational. Peak Horizontal Ground Acceleration (PGA) will be used for quantifying the seismic hazard at different return periods incorporated as a pseudo-static coefficient in the slope stability analyses. The slide width will be determined on candidate slope basis. Where applicable, the excess pore pressure generated will be treated as a coefficient in the cohesionless strata. The commercially available program, SLIDE or SLOPE/W, will be used. The slope stability analyses will provide the volume of moving soil and water depth to the center of the sliding mass.

For acceleration of the failed mass, Grilli et al., 2009, used semi-empirical equations based on two- and three-dimensional numerical simulations of a sliding block in similar studies. While their approach will be implemented, the method developed by Imran et al. (2001) is proposed to establish the relationship between the initial mass acceleration (during the early mass movement) and mass volume. This method is based on the flow characteristics (i.e. rheological properties) of the failed mass. The advantage of this method is that later it could be extended to investigate the maximum velocities and run-out distances of potential slides.

C) Hydrodynamic Set-down Model:

Statistical distributions describing the slope stability analysis will be used to derive the hydrodynamic initial wave configuration. However, because of the computational intensity of a conventional wave model to generate the initial wave (eg. a 3D Navier-Stokes model) is prohibitive to simulate in each landslide individual MCS. Instead, a deterministic and simplified hydrodynamic calculation will be completed for a very large number of pre-specified fractiles of the distributions of the volume, acceleration and depth of the mass failure, with each calculation computing a single maximum depression of the free surface for a single combination of volume of moving soil, acceleration of that volume and water depth. The pre-specified combinations of fractiles will comprehensively span the complete range of slope stability failures such that the initial depression of the free surface will be computed for any combination of these three parameters. The resulting database can then be used in place of the hydrodynamic wave model in the MCS procedure for each of the estimated 40 locations on the GOM's continental shelf.

The final result of this MCS effort is a complete statistical distribution of the maximum depression of the free surface for each of the ~40 locations.

D) Hydrodynamic Wave Model

The computational hydrodynamic wave model is similar to or just slightly less computationally intensive than a conventional model for calculation of the maximum depression of the free surface due to a landslide. Each location of a potential landslide is sufficiently unique that building a complete database for use in MCS simulations is not realistic. However, it is well known that there is a direct correlation between the initial set-down that initiates a tsunami wave and the severity of the ensuing tsunami, Geist *et.al*., 2009. The fractile of the set-down at a specific location is equal to the fractile of the tsunami originating at that location, i.e. the 500-year set-down at a specific location causes the 500-year tsunami originating at that location. Here, that correlation will be directly applied, so pre-specified fractiles of tsunamis originating at each of the about 40 locations can be computed directly using the wave propagation model, without need to execute the numerous computationally-intensive wave propagation model in MCS. Then, the wave propagation and runup simulations will be conducted for that set of near-field and far-field tsunami sources for which the probability of occurrence have been estimated.

From the sediment stability model, the sediment-slope than has been considered unstable for a specified seismic acceleration, the initial maximum depression of the free surface (sources) is determined by a set of simplified and empirical equations.

The initial wave configuration (wave depression) will be based on two empirical relationships that predict the initial tsunami amplitude based on the landslide main parameters described in section B. Each failure obtained from the sediment-slope stability model is characterized as either translational or rotational, after which an initial tsunami characteristic amplitude η_o will be determined, Grilli andWatts, 2001; Grilli et al., 2002; Grilli and Watts, 2005; Watts et al., 2005a. For landslide tsunamis, η_o is defined as the maximum depression of the free surface above the submarine landslide geometrical center and given by,

$$\eta_{oT} = S_{oT}(0.0574 - 0.0431\sin\beta)\left(\frac{T}{l}\right)\left(\frac{l\sin\beta}{d}\right)^{1.25}(1 - e^{-2.2(s-1)})\left(\frac{w}{w+\lambda_{oT}}\right)$$

for the traslational; and

$$\eta_{oR} = S_{oR}\left(\frac{0.131}{\sin\beta}\right)\left(\frac{T}{l}\right)\left(\frac{l\sin\beta}{d}\right)^{1.25}\left(\frac{l}{r}\right)^{0.63}(\Delta\phi)^{0.39}(1.47 - 0.35(s-1)(s-1)\left(\frac{w}{w+\lambda_{oR}}\right)$$

for the rotational; where *d* is the depth below sea level above the center of the failed mass, *w* the failure width, $\Delta\Phi$ the maximum angular displacement, *r* radius of the rotational failure, S_{oR} and S_{oT} the characteristic distance of motion for translational and rotational failures, λ the characteristic tsunami wavelength. More details regarding the these empirical relationships can be found in Grilli andWatts, 2005 and Enet and Grilli, 2007.

The wave propagation and runup will be carried out by the 2D non-hydrostatic and hydrostatic model developed by the University of Alaska Fairbanks (UAF) and the University of Hawaii (UH), NEOWAVE for Non-hydrostatic Evolution of Ocean WAVE. NEOWAVE is built on the nonlinear shallow-water equations with a non-hydrostatic pressure term to describe

weakly dispersive waves. The model is equivalent to existing models based on the classical Boussinesq equations. The code has been tested showing very good agreement (see Yamazaki, Kowalik and Cheung, *et.al*, 2009) with benchmark cases for tsunami model validation and verification described in the report OAR PMEL-135, Synolakis, *et.al,* 2007.
The code features a momentum conserved advection scheme that enables the modeling of breaking waves without the aid of analytical solutions for bore approximation or empirical equations for energy dissipation. An upwind scheme extrapolates the free surface elevation instead of the flow depth to provide the flux in the momentum and continuity equations. The pressure term is split into hydrostatic and non-hydrostatic components, and the vertical velocity is introduced in response to the non-hydrostatic pressure through the three dimensional continuity equation. Additional model features are: a) a robust momentum conservation scheme; b) nesting capability necessary for finer resolution in the runup zone domain; c) breaking and shock wave discontinuity. Since the numerical scheme for the momentum and continuity equations remains explicit, the implicit non-hydrostatic solution (dispersion) requires a solver for the linear system of equation solution, which is very computing demanding; therefore, it is here where the code optimization should take place to handle a reasonable numerous number of calculations. It is known that a underwater landslide generated tsunami usually falls in the intermediate water wave regime. The back-going tsunami wave generated by an underwater landslide immediately reaches the continental shelf and after some wave transformation (fission) as it passes the shelf-break the resulting waves become a shallow water wave. At this point a dispersive model (after the point of wave transformation due to shelf-break) is not longer required in shallow region. Because it is planned to perform a lesser but not small number of computer runs for wave propagation and runup, an optimization to the current NEOWAVE code needs to be implemented. The implementation will be carried out by switching off the non-hydrostatic pressure calculation (the dispersion code portion) by means of a field domain variable (sensor) that can be controlled by computer run time or by the detection of the wave regime in the area of interest.

In summary, the major tasks to obtain hydrodynamic solution are: 1) the creation of a simplified model which transforms the sediment-slide characteristic to an initial wave configuration or source (wave amplitude, wave length and lateral extent, etc). 2) the optimization of an existing tsunami non-hydrostatic and hydrostatic model for fast and efficient calculation of waves propagation and runup.

Project Benefits

The strategic plan of the NTHMP program recommends that program resources be weighted appropriately between activities that improve the level of community preparedness and the state of tsunami science. The NTHMP Performance Measures and Milestones include a strategy to *"support a research effort to develop U.S. tsunami hazard assessment methodologies"* in order to *"develop quantitative tsunami hazard analysis techniques including source determination and probability of occurrence"*.
This effort primarily will benefit the activities and strategic goals of the NTHMP and the public by contributing to the outcomes of the NTHMP in the area of tsunami mapping, modeling, mitigation, planning and education. Project results will enable local authorities to plan for

tsunami case scenarios in addition to storm surge effect and provide guidance to optimize real-time warnings to communities on the GOM coastline.
At the core of this project is a balance between education and tsunami science. Two post doctoral graduate students will be supported and involved in the research on submarine landslide probabilistic approach. This is a priceless opportunity for the students, likely to become the next generation of tsunami researchers. This type of work will help students to systematically understand physics associated with this phenomenon and contribute to the tsunami science, and to address the physical processes within the probabilistic framework.

Research team background:

The study will be carried out by a qualified team of research professionals with a proven track record on hazard assessment, tsunami and underwater slope stability modeling.

The team will be led by Dr. Horrillo. Dr. Horrillo is an expert on tsunamis, ocean waves and their impact on coastlines. He has been recently involved in a NTHMP, NOAA project to built the first comprehensive tsunami inundation map for the GOM coastline. He has been doing tsunami research for more than 10 years, Dr. Horrillo is the NTHMP technical representative for the GOM's states and is an active contributor to the US Tsunami Warning Centers. At Texas A&M University, Galveston, his research focuses on underwater landslide induced-tsunami with interest on soil rheology and its effects in the generation of tsunami waves. His other research areas, all involve computational fluid dynamics of ocean waves. He has developed an efficient 3D tsunami numerical model in collaboration with the University of Alaska Fairbanks, the first in its class, to calculate tsunami waves generated by submarine landslide for practical application. His duties and contribution in this project will be: a) the coordination and assembling of multidisciplinary tasks and provide an organizational framework for the team effort; b) oversee project production and ensure project tasks are moving forward; c) to drive the project process to successful completion by adjusting or adapting resources accordingly to the project's timelines, plans, milestones and outlines. d) creation of a simplified model which transforms the sediment-slide characteristic to an initial wave configuration or source and f) the optimization of an existing tsunami non-hydrostatic model for fast and efficient calculation of waves propagation and runup.

Dr. Sweetman is a well known expert in random processes and in statistical prediction of extreme values in non-linear dynamic systems subject to random processes. He also applies advanced statistical methods to better understand irregular environmental loading on offshore structures. He has completed numerous studies on floating structures for various offshore projects around the world. He has extensive experience on wave statistical interacting with floating structures, and in the developing of new methodologies which apply random vibration theory to better understand vortex induced vibration in steel catenary risers. Dr. Sweetman's contributions in the project are: a) to develop the probabilistic tsunami hazard assessment main methodology; b) the parametric statistical study to determine the most important physical parameters for extreme values of tsunami initiation source; c) the determination of the distribution of the physical parameters and the analytical combination of the random variables using random variable algebra, and d) performing the statistical combination of tsunami events caused by multiple landslides.

Dr. Zakeri is a well known international expert in geotechnical engineering fields. He has been intensively involved on offshore geo-hazards study, Computational Fluid Dynamics (CFD) analysis, specialized geotechnical / foundation analysis and modeling including stability of natural and embankment slopes, settlement estimation and foundation (deep and shallow) design, liquefaction potential evaluation, earthquake effects and seismic/dynamic stability of earth dams, assimilation of geotechnical data / information and site characterization. Further application of his expertise has been on estimation of drag forces on pipelines and seafloor structures caused by a submarine debris flow and turbidity current impact. The primary efforts of Dr. Zakeri on this project are: a) assembling a comprehensive soil database for underwater landslide in the GOM and b) to develop a 2D simplified slope stability analyses for the generation of extreme values of the initial tsunami wave configuration.

Charles Williams is the Division Chief for the Preparedness Division with the Alabama Emergency Management Agency. He is the NTHMP emergency manager representative for the GOM states. Mr. Williams has been involved in response and preparedness efforts for Twenty-nine presidential declared emergencies, Deepwater Horizon, and numerous state and locally declared disasters during his 17-year tenure with the Alabama Emergency Management Agency. The Preparedness Division consists of the Planning Branches, which includes the Chemical Stockpile Emergency Preparedness Program (CSEPP), Mitigation, Terrorism, Radiological, Natural Hazards (storm surge and tsunami), and Technical Hazards. Mr. Williams will serve as an emergency manager consultant to ensure research efforts are relevant to practical application for response and preparedness strategies.

Summary of Task Plan

This project will facilitate state emergency and land-use managers in their efforts for evaluation of new or existing developments on risk tsunami zone and to conduct realistic response preparation, evacuation strategies, and education efforts. This attempt will center only on tsunami-related hazards associated with earthquake which can trigger underwater landslides that can generate a near-field tsunamis.

1- Report documenting the submarine landslide tsunami hazard analysis tools.
2-Application of the hazard analysis tools to the GOM's northwestern region (South Padre Island -Galveston, TX.).
3- GOM's sediment/soil parameters (geo-dataset) assimilated from publically available information and determined from laboratory testing in form of a database for slope stability and debris flow analyses and ultimately, tsunami modeling.
4- Probabilistic tsunami runup model output data and products
5- Simplified 2D sediment/soil slope stability analysis and debris flow model
6- Fast-optimized 2D shallow water numerical code for wave propagation and runup.
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8- Site-specific 100, 500 and 10000 years annual exceedance values (runup height)
9- locations and characterization of most likely tsunami scenarios (tsunami sources) associated to potential landslide events with probability of recurrences
10- At least two publications in recognized journal papers in joint probabilities

Performance Period

The duration period to complete this project is 2 years, from August /2012 to July /2014

Budget

Project Name: A probabilistic methodology for hazard assessment of tsunami generated by subsea landslide for tsunami mapping in the Gulf of Mexico
Project Dates: August /2012 to July /2014
Principal Investigator: Juan J. Horrillo
CO-PIs: John Sweetman, Arash Zakeri and Charles Williams

Component 1: Tsunami mapping	FY12	FY13
SALARY		
PI	2 months	1 month
Salary	$17,185	$8,850
Fringe Benefits, Health Insur. Etc.	$3,904	$1,996
CO-PI	2 months	1 month
Salary	$17,570	$9,049
Fringe Benefits, Health Insur. Etc.	$3,970	$2,030
2 Postdoc Students	1 Year	1 Year
Salaries	$80,000	$82,400
Fringes Benefits, Health Insur. Etc	$25,136	$25,548
EQUIPMENT		
Computer (12Gb+8CPU) & supply, UPS, etc.	$4,500	$1,000
TRAVEL		
Meeting Travels (4 days)/ year	$3,000	$3,500
Conference Travel (3 day)/year	$2,500	$2,500
CONTRACT C-CORE		
CO-PI Geophysics /Soil Mech.	2 months	1 month
Support	$21,000	10,500
Student		
Support for soil data acquisition and compilation	$15,000	
Travel	$3,000	
OTHERS DIRECT COSTS		
Publication Cost	$2,000	$2,000
Total Direct Cost	$198,765	$149,373
Texas A&M University Indirect Cost (46.5%)	$85,916	$64,576
Total Proposal Cost	$284,681	$213,949

TOTAL	$284,681	$498,630

Budget Justification (See Budget Narrative Document)

References

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Grilli, S.T.,Watts, Ph., 2001. Modeling of tsunami generation by an underwater landslide in a 3D-NWT. Proc. 11th Offshore and Polar Engng. Conf. (ISOPE01, Stavanger, Norway, June 2001), vol. III, pp. 132–139.

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Grilli, S.T., Watts, P., 2005. Tsunami generation by submarine mass failure. I: modeling, experimental validation, and sensitivity analyses. J.Waterw. Port Coast. Ocean Eng. 131 (6), 283–297.

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Grilli, S. T., Taylor, O.-D. S., Baxter, C. D. P. and Maretzki, S. (2009). "A probabilistic approach for determining submarine landslide tsunami hazard along the upper east coast of the United States." Marine Geology 264(1-2): 74-97.

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Maretzki, S., Grilli, S.T. and Baxter, D.P. 2007. Probabilistic SMF Tsunami Hazard Assessment for the upper East Coast of the United States. In *Proc. 3rd Intl. Symp. on Submarine Mass Movements and their Consequences* (Santorini, Greece, October 2007) (Santorini, Greece, October 2007) (Lykousis, V., Sakellariou, D., Locat, J., eds), Springer, 377-386

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Watts, P., Grilli, S.T., Tappin, D.R., Fryer, G.J., 2005a. Tsunami generation by submarine mass failure. II: predictive equations and case studies. J.Waterw. Port Coast. Ocean Eng. 131 (6), 298–310.

VITAE

Juan J. Horrillo
e-mail: horrillj@tamug.edu
Maritime Systems Engineering
Texas A&M University at Galveston
PMEC 217
Galveston, Texas, 77553
phone: (409) 740 4465

EDUCATION

Postdoc. in Tsunami
University of Alaska Fairbanks, USA (May, 2006)

PhD. Physical Oceanography (Tsunami)
University of Alaska Fairbanks, USA (April, 2006)

Tsunami Student Exchange
Tohoku University, Japan (June-September, 2003)

MS Ocean Engineering
University of Rhode Island, USA. (April, 1997)

BS Civil Engineering
University of Cartagena, Colombia. (1984)

EXPERINCE

Assistant professor
Texas A&M University at Galveston (Sep, 2008-)

Research fellow
University of Alaska Fairbanks, (2006 - Aug 2008)
Research in tsunami numerical modeling (hydrostatic non-hydrostatic models)

Research assistant.
University of Alaska Fairbanks, (2002- 2006)
Research in tsunami numerical modeling using full Navier-Stokes equations and the Volume of Fluid method to track the free surface.

Marine design engineer.
Instituto Mexicano del petroleo, engineering division, Mexico (1998-2001)
Develop of risk assessment criteria and site characterization of oceanographic parameters for offshore platforms and submarine pipelines (PEMEX).

Research assistant.
University of Rhode Island, (1995-1997)
Research in numerical modeling of nonlinear waves shoaling over slope using Boundary Element Method.

Ocean/Civil engineer
Colombian petroleum Co. (ECOPETROL), Colombia, (1986-1992)
Structural design, cost estimation, bid evaluation, structure maintenance, work supervision. On-site construction/inspection of structural projects (steel, timber, concrete) in marine and ocean environments. Projects: Ports, marinas, bridges, oil tank dikes, barge docks, etc.

PUBLICATIONS

Horrillo, J., Knight, W., and Z. Kowalik 2008 The Kuril Islands Tsunami of November 2006. Part II: Impact at Crescent City by local amplification**.** *J. Geoph. Res.* 113, C01021, doi:10,1029/2007JC004404.

Kowalik, Z., Horrillo, J., Knight, W., and T. Logan 2008 The Kuril Islands of November 2006. Part I: Impact at Crescent City by distant scattering, *J. Geoph. Res.* Research, 113, C01020, doi:10,1029/2007JC004402.

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Soreano, A., Marino, I., Horrillo, J. and Ramos, R. 1999. " Condiciones Oceanograficas para el Diseno de Lineas Submarinas en la Region Norte." En Memorias del 4° Congreso y Expo Internacional de Ductos. Boca del Rio, Veracruz, Mexico.

Horrillo, J. y Villalba, R. 1999. " Estabilidad Hidrodinamica ". Memorias del Taller de Aplicacion del Criterio Transitorio para Evaluacion de Tuberia Submarina en la Sonda de Campeche. Instituto Mexicano del Petroleo y Petroleos Mexicanos. Mexico, DF.

Grilli, S.T. and Horrillo, J. 1998 "Computation of periodic waves shoaling over barred-beaches in a fully nonlinear numerical wave tank". In Proc. ISOPE98 (ISOPE98, Montreal, Canada, May 1998) (ed. Chung, J.S., Olagnon, M., Kim, C.H., Koterayama, W.), Vol. III, pp 294-300. Intl. Society of Offshore and Polar Engng., Golden Colorado.

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Grilli, S.T. and Horrillo, J. 1997 " Numerical Generation and Absorption of Fully Nonlinear Periodic Waves". Journal of Engineering Mechanics, 123(10),1060-1069.

Grilli, S.T. and Horrillo J. 1997 Fully Nonlinear Properties of Shoaling Periodic Waves Calculated in a Numerical Wave Tank. In *Proc. 12th Intl. Workshop on Water Waves and Floating Bodies* (Carry-Le-Rouet, France, March 97),

Grilli, S.T. and Horrillo J. 1995 Numerical Modeling of Wave Breaking on Beaches and over Coastal Structures. In *Proc. 2nd. Intl. Conf. on Computer Modeling of Seas and Coastal Regions* (COASTAL95 Cancun, Mexico, September 1995)(eds. C.A. Brebbia, L. Traversoni and L.C. Wrobel), pps. 151-158. Computational Mechanics Publications, Boston. (invited paper).

John A (Bert) Sweetman PE, PhD
Associate Professor, Maritime Systems Engineering
Texas A&M University at Galveston
200 Seawolf Parkway Galveston, TX 77553
sweetman@tamu.edu

Professional Preparation

University of Michigan
Naval Architecture and Marine Engineering
Bachelor of Science in Engineering, 1986

Texas A&M University
Ocean Engineering
Master of Engineering, 1987
Advisor: Jack Lou

Stanford University
Civil and Environmental Engineering
Doctor of Philosophy, 2001
Advisors: Cornell and Winterstein

Stanford University
Statistical Methods in Structural Dynamics
Postdoctoral Research, 2001–2002
Advisor: Allin Cornell

Present Appointments

Associate Professor, Maritime Systems Engineering Department (MASE), Texas A&M at Galveston

Joint Appointment with Texas A&M in College Station:
Associate Professor, Civil-Structural Engineering
Associate Professor, Coastal and Ocean Engineering

Prior Appointments

Assistant Professor, Maritime Systems Engineering Department (MASE), Texas A&M at Galveston (Hired January 2003).

Joint Appointment with Texas A&M in College Station:
Assistant Professor, Civil-Structural Engineering (Since September 2005)
Assistant Professor, Coastal and Ocean Engineering (Joint Grad. Appt. since January 2003)

Doctoral and Post-Doctoral Studies at Stanford University (1996–2002).

Research Engineer in Mobil Oil's division responsible for offshore engineering (1986 - 1996). Various positions including specialist in hull structures, vessel dynamics, marine risers, fluid-structure interaction and project management.

Present Teaching

CVEN 221: Statics and Particle Dynamics
MASE 301: Hydrodynamics of Offshore Strucutures
MASE 406 and MASE 407: Design of Ocean Structures (Capstone I and II)

Prior Teaching

CVEN 346/446: Structural Steel Design
MASE 467 / OCEN 689 (stacked): Offshore Random Processes

Funding

NSF: Floating Offshore Wind Turbines: Conceptual Assessment of Highly Compliant Plat- forms Using Theory, Design and Simulation. PI. September 2011 – August July 2014. $300,000.

NSF: U.S.-Germany Planning Visit: Structural Health Monitoring Sensors for Offshore Wind Turbines. Co-I, with PI Jerry Lynch at University of Michigan April 2008 – March 2009. Total budget: $10,146. Sweetman portion: $2,568.

Texas Institute of Oceanography: Funding for Postdoctoral Fellow Kim Mittendorf. Septem- ber 2006 – September 2008. PI. Approx $100,000.

Texas Institute of Oceanography: Funding for Undergraduate Research Opportunity. PI. April 2006 – April 2007. $3,000.

NSF: CAREER: Irregular Environmental Loading and Response of Offshore Structures PI. August 2005 – July 2011. $400,000.

NSF: Sensors: Statistical Algorithm Development for Distributed Sensor Networks with Ap- plication to Structural Health Monitoring and State Assessment. PI, with Co-I Lucianna Barossa at Texas A&M College Station. September 2005 – August 2008. Total budget: 157,441. Sweetman Portion: $78,271.

NSF: REU Supplement: Sensors - Statistical Algorithm Development for Distributed Sen- sor Networks with Application to Structural Health Monitoring and State Assessment. PI. September 2005 – August 2008. $6,000.

Students Advised:

Committee Chair: Lei Wang, PhD Student in Ocean Engineering, September 2008 – Present.

Myoungkeun Choi, PhD Candidate Civil-Structural Engineering, September 2003 – Gradu- ation Spring 2009.

Mahdi Karimi, Initially PhD student in Ocean Engineering but failed Doctoral Qualifying Exams. Graduated with Masters of Engineering December 2008.

Committee Member:

Justin Jackson, Master of Science in Aerospace Engineering, 2008.

Meghan Hull, Master of Science in Ocean Engineering, 2006.

Kieth Dupuis, Master of Science in Oceanography, 2005.

Post-Doctoral Researcher:

Kim Eric Mittendorf. PhD from University of Hanover, Germany. Expertise in environ- mental loading on offshore wind turbines. Left for permanent employment after 13 months (November, 2007).

Patents

Fairing for Marine Risers. US Patent Number 5,722,340. Approved: March 3, 1998. In- ventor: Sweetman, John A., Patent is for a vortex-induced vibration suppression system for marine drilling risers.

Floating Barge-Platform and Method of Assembly. US Patent Number 6,125,780. Approved: October 3, 2000 Inventors: Sweetman, John A., Gu, George Z., Garrett, David L., Patent is for a unique offshore liquified natural gas (LNG) production facility.

Journal Papers (Most papers available at www.rms-group.org/RMS Papers)

Wang, L., and Sweetman, B. "Simulation of Large-Amplitude Motion of Floating Wind Turbines Using Conservation of Momentum" Ocean Engineering, Accepted August, 2011.

Sweetman, B. and Wang, L., "Floating Offshore Wind Turbine Dynamics: Large-Angle Motions in Euler-Space" Journal of Offshore Mechanics and Arctic Engineering, OMAE-10- 1056, April 2011.

Swartz, R.A., Lynch, J.P. Zerbst, S., Sweetman, B., and Rolfes, R., "Structural Monitoring of Wind Turbines using Wireless Sensor Networks" Smart Structures and Systems, Vol. 6, No. 3, 1–18. June of 2010.

Choi, M. and Sweetman, B., "The Hermite Moment Model for Highly Skewed Response with Application to Tension Leg Platforms" ASCE Journal of Offshore Mechanics and Arctic En- gineering, for May 2010, Volume 132, Issue 2.

Sweetman, B and Choi, M., "The Modal Distribution Method for Statistical Analysis of Measured Structural Response" Journal of Probabilistic Engineering Mechanics, In Press; available online November 2009.

Choi, M. and Sweetman, B., "Efficient Calculation of Statistical Moments for Structural Health Monitoring" Journal of Structural Health Monitoring, January 1, 2010, Vol. 9, No. 1, 13–24.

Mittendorf, K., Sweetman, B. and Zielke, W. "Wave Climate Hindcast for the Design of Offshore Wind Energy Structures in the German Bight" International Journal of Ecology & Development, IJED Special Issue on the Coastal Environment. 2007.

Sweetman, B., "Practical Airgap Prediction for Offshore Structures." ASME Journal of Offshore Mechanics and Arctic Engineering, Vol. 126, Issue 2, 147–155, May 2004

Sweetman, B. and Winterstein, S. R. "Non-Gaussian Air Gap Response Models for Floating Structures" ASCE Journal of Engineering Mechanics, Vol. 129, Issue 3, pp 302–309 March 2003. [Also presented orally: OMAE 2000, Stavanger Norway].

Sweetman, B., Winterstein, S. R., and Meling, T. S. "Air Gap Prediction from Second-Order Diffraction and Stokes Theory." International Journal of Offshore and Polar Engineering, Vol. 12, No. 3, Sept 2002.

Sweetman, B., Winterstein, S. R., and Cornell, A. "Airgap Analysis of Floating Structures: First- and Second-Order Transfer Functions from System Identification" Elsevier: Applied Ocean Research, Vol. 24, Issue 2, 107–118, April 2002.

Winterstein, S. R., and Sweetman, B. "Air Gap Response of Floating Structures: Statistical Predictions vs Observed Behavior" ASME Journal of Offshore Mechanics and Arctic Engi- neering. Vol 123, August 2001, pp. 118-123 [also presented orally OMAE 1999, New Orleans Louisiana]

Manuel, L., Sweetman, B., and Winterstein, S. R., "Analytical Predictions of the Air Gap Response of Floating Structures," Journal of Offshore Mechanics and Arctic Engineering, Vol 123, Page 112-117, August 2001.

Budget Narrative

Project Name: A probabilistic methodology for hazard assessment of tsunami generated by subsea landslide and for construction of tsunami inundation maps in the Gulf of Mexico
Project Dates: 08/01/2012 – 07/31/2014
Principle Investigator: Juan J. Horrillo
CO-PIs: John Sweetman, Arash Zakeri and Charles Williams

Component 1: NTHMP	FY12	FY13
PI and Co-Pi Personnel	$34,755	$17,899
Fringe Benefits	$7,874	$4,026
2 Postdocs Students	$80,000	$82,400
Fringe Benefits	$25,136	$25,548
Equipment	$4,500	$1,000
Travel	$5,500	$6,000
Publications Cost	$2,000	$2,000
Contract C-Core	$39,000	$10,500
Total Direct Costs	$198,765	$149,373
Indirect Costs	$85,916	$64,576
Total Cost Proposal	**$284,681**	**$213,949**

Total Amount of Award: $ 498,630

Justification of the Budget

Personnel:

The PI's responsibility will be the coordination and assembling of multidisciplinary tasks, the creation of a simplified model which transforms the sediment-slide characteristic to an initial wave configuration or source and the optimization of an existing tsunami non-hydrostatic model for fast and efficient calculation of waves propagation and runup.

The CO-PI's responsibility will be to develop the probabilistic tsunami hazard assessment tools in general; to perform the parametric statistical study to determine which specific physical parameters are most important for extreme values of tsunami initiation source; the determination of the distribution of the physical parameters and the analytical combination of the random variables using random variable algebra.
The primary effort of Dr. Zakeri is to assembling a comprehensive geo-dataset for underwater landslide in the GOM and to develop a 2D simplified slope stability analyses for the generation of extreme values of the initial tsunami wave configuration.

Postdoc Students:
The two Postdocs will be in charge of assembling the basic methodology for the probabilistic approach. This team will be gathering the available geotechnical parameters necessary for the characterization of soil by region in the GOM; building the geotechnical database needed for slope stability analysis; setting computer inputs, batch jobs for all possible combinations of the

distributed physical parameters and doing the post-processing required for journal papers, meetings and conferences. The student team will be supporting in establishing the formal methodology and conducting a probabilistic tsunami hazard assessment to identify potential submarine landslides with the higher probability of generating a tsunami. The work includes the analysis of the statistical study to determine which specific physical parameters are most important for probabilistic hazard assessment and combine them with the deterministic stability slope analyses for underwater sediments and with the hydrodynamic model for wave propagation and runup.

Salary and Fringe Benefits

PERSONNEL	FY12	FY13
PI: Dr. Juan Horrillo	2 months	1 month
Salary	$17,185	$8,850
Fringe Benefits, Health Insur. Etc.	$3,904	$1,996
CO-PI-1: Dr. John Sweetman	2 months	1 month
Salary	$17,570	$9,049
Fringe Benefits, Health Insur. Etc.	$3,970	$2,030
2 Postdoc Students	1 Year	1 Year
Salary	$80,000	$82,400
Fringe Benefits, Health Insur. Etc.	$25,136	$25,548

Fringe Benefits:

Fringe benefits are calculated at 17.2% of salary requested plus $474 per month for insurance.

Equipment:

A high performance computer workstation is required: 1- to perform massive batch calculations for the MCS; 2- to perform deterministic analyses (submarine slope stability and the tsunami hydrodynamic); 3- to develop a geo-dataset consisting of soil parameters for present and future use; and 4- to integrate in one computer unit all project products and information.

MATERIALS & SUPPLIES Computer (12Gb+8CPU) & supply, UPS, etc.	$4,500	$1,000

Travel:

Travels are required for project team members to report, discuss results and/or for numerical tools training. It is foreseen one meeting per year for one member of the team to report and discuss methodologies adopted. In addition several short trips or visits to nearby companies are required to gather soil data information. Provisions have been made in the budget to assist key members other than NTHMP representatives to attend NTHMP's annual meetings or conferences that contribute in adding value to the project work.

TRAVEL	FY12	FY13
Meeting Travels (4 days)/ year	$3,000	$3,500
Conference Travels (3 days)/ year	$2,500	$2,500

Contract C-Core:

The budget for CO-PI is based on salary plus 35% payroll burden. The estimated level of effort is two months in FY12 and one month in FY13. The budget for the Post-doc is based on salary plus 13% MERC (Mandatory Employer Related Costs).

PERSONNEL	FY12	FY13
CO-PI-2 (CONTRACT): Dr. Arash Zakeri Support	2 months $21,000	1 month $10,500
Post-doc Support	2 months $15,000	---- ----

An additional CO-PI Dr. Zakeri travel is required for C-Core to present Geo-data set findings and geo-technical methods adopted for landslide characterization. The estimated cost for the Dr. Zakeri is based on following assumptions: from St. John's, NL to Galveston, Texas:

Duration: 5 days
Airfare: $1,200
Accommodations: $1,000
Rental Car: $300
Per Diems: $500
Total: $3,000

Total External Contract Cost: FY12= 39,000
FY13=10,500

Indirect Costs:

Indirect costs are calculated at the Texas A&M University DHHS rate of 46.5% of Modified Total Direct Costs (less subcontract costs greater than $25,000).