

3D Physical Model of Tsunami Inundation Over a Complex Bathymetry

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Abstract:

Tsunami inundation data, including wave height and near offshore velocity, were collected over a complex bathymetry in the O.H. Hinsdale Wave Research Laboratory in an existing bathymetry using four capacitance wave gages and four acoustic-Doppler velocimeters to create a benchmark set of data for numerical models of tsunami inundation. Four different wave types (two at 55 cm still water depth and two at 44 cm still water depth) were run for 288 total X,Y locations in North, South, and Harbor regions of the tsunami wave basin. Preliminary time series plots for maximum wave height and maximum horizontal wave velocity are presented. Maximum horizontal wave velocity is represented for the four wave types in plotted vector grid figures for comparison. Future data are to be collected using a particle image velocimetry (PIV) system for shallow water depth velocities and a pressure transducer array for tsunami inundation impact pressure. All data will be placed online as part of the shared-use concept of the National Science Foundation's Network for Earthquake Engineering Simulation program.

1. Introduction

Recent tsunami events have emphasized the need for a better understanding of general tsunami characteristics. Tsunami events occur in three phases. First is the initial tsunami generation, widespread tsunamis being caused by deep sea floor movements and shifts and local tsunamis being generated by volcano eruption, landslides, and various local impacts. It should be noted that these are not always the sole causes for generation, and often times it may be a combination of any number of these conditions. The second phase of a tsunami event is its propagation from the generation site to the coastline. In the deep sea setting, tsunami waves are very long but not necessarily reaching extreme heights. The propagation speeds of a tsunami can be almost 500 miles per hour, as fast as a commercial airline. It is the third phase of a tsunami event, inundation, where the greatest interaction between tsunamis and human life and activities occurs. As a tsunami reaches the shallower coastline it begins to slow in speed and build in height. Because tsunami waves and waves in general conserve energy and build until breakpoint, tsunami waves will reach much greater heights and cause the greatest damage on the coast instead of the open sea. Tsunami inundation, as opposed to generation and propagation, is the main concern in a coastal engineering mindset because of its affect on the coastal population.

Numerical modeling of tsunamis aims to provide tools that assist in tsunami awareness, preparation, and response. However, because field data are limited, laboratory data are needed to verify (or refute) these numerical models. An extensive literature research and review was completed in order to gain a better view of existing field, laboratory, and numerical testing that has been performed and discover what types of research are needed to aid in better understanding of tsunami inundation.

1.1 Literature review

A total of fifteen publications were analyzed for applicability to this study. Five of the most applicable articles to this study are presented. The following review is formatted with one paragraph of subjective review and added relevance of the literature study to the proposed experiment.

The research presented in Briggs et al (1995a) involves the collection of wave characteristic parameter data through an experiment running solitary waves at a circular island. A basin 25m by 30m with water depth at 32cm was equipped with 27 capacitance wave gages to measure wave height. A survey rod and transit measured vertical wave run up maximums. Three cases A, B, and C of target wave heights of 5, 10, and 20cm respectively were tested. The data set from the various gages was collected and plotted both gage by gage and case by case. The run-up of solitary waves on a circular island provides a premise for the experimental aspect of laboratory tsunami modeling and is referred to as a preliminary, initial study of tsunami inundation.

Briggs et al (1995b) study of large scale three dimensional tsunami inundation contributes significance to the proposed experiment. Three dimensional tsunami inundation was presented as an experiment utilizing both a long wave flume and a large wave basin. Solitary waves were ran with capacitance wave gages and laser Doppler velocimeters to measure wave evolution, uniformity, run up, and wave kinetics such as horizontal velocity

variation with depth, run up velocity, maximum vertical run up, and run up velocity. A comparison of flume and basin data sets and results revealed an almost linear increase of run up with increased generation length, and the non-breaking waves in the basin were lower than in the flume. The purpose of the study was to validate numerical models, and a detailed description of the basin is provided. In-depth description of the instrumentation (including physical characteristics) is given. This type of format will be essential to the proposed tsunami inundation study.

Because impact pressure is to be considered in the proposed study, Hamzah et al (2000) hydrodynamic pressure on a tsunami barrier experiment is applicable. Bore type broken solitary waves were impacted into a wall representing a simplistic tsunami barrier. Stressed is the numerical analysis involved to represent a dam break problem and a run up/run down of a solitary wave on a gentle slope. A wave flume and barrier wall at the top of a gentle slope was equipped with five pressure transducers recorded data to produce a 3-D simulation of wave observations and recorded pressure gradients. Resulting are two pressure peaks of impulsive pressure followed by standing wave pressure. The flume, barrier, and instrumentation diagrams are very effective at conveying the experimental setup. However, the proposed study differs from the Hamzah study because all data will be collected rather than observed.

The report presented by Liu et al (1991) provides the overall scope of why a study such as this is necessary. Presented were various laboratory experiments, numerical prediction models, and field observations. Discussed for laboratory experiment were proposals to explore physics of run up and confirm/refute numerical models. Scale effects are minimized with large scale models, and three different run up processes were identified as smooth and unbroken, overturning bore onto dry bed, and transient processes, all of which produce different maximum run up heights. In numerical modeling, detailed initial conditions, accurate 3-D bathymetry data, and wave characteristic data sets are needed. A real tsunami time system was discussed and agreed upon that it would be necessary for tsunami inundation response. Field observations detailed some conflicts in theory and observation and studies of tsunami zoning (both site specific and source specific) were needed for proper awareness and response. The Liu et al paper stresses the question of “what do we, as tsunami researchers, need to do in order to effectively mitigate tsunami problems?” It was agreed that 3-D modeling and lab data sets promise better results for numerical modeling. Boundary conditions and layer theory found within fluid dynamics are very difficult, and model improvement in 3-D bathymetry is the essential “next step” for state-of-the-art modeling. With the completion of this study, a collective data set from a complex bathymetry will be available for numerical models.

An example of such numerical modeling is presented in the numerical modeling experiment presented by Titov et al (1998). Large earthquakes and tsunamis prompted the study of numerically modeling tsunami run up. While 1+1 (one propagation at one time) run up is rather basic to model, 2+1 (two propagations at one time) are more difficult. Using a splitting technique, a 2+1 becomes two simultaneous 1+1 problems. This numerical inundation model is validated by large scale physical models of Briggs et al. Boundary conditions (fixed) provide for accurate boundary value problem modeling, but a moving boundary is required for the tip of a shoaling wave. With a finite difference scheme, it is recognized that a uniform grid (in computational domain) loses accuracy near shore with

non-consistent resolution. Concluding, it is stressed that both bathymetric and topographic data sets (resolution) and inundation velocity data are needed for accurate numerical modeling. The numerical model is validated with several physical models and compared to field observations. A joint cooperation of field, laboratory, and numerical modeling equip scientists and engineering with the tools necessary to understand tsunami inundation.

2. Proposal

The three dimensional physical model of tsunami inundation was performed. A comprehensive data set, with emphasis on velocity parameters and complex bathymetry, was collected in the Oregon State University O.H. Hinsdale Wave Research Laboratory in the tsunami wave basin. The basin was expanded in 2003 by a 4.8 million dollar grant from the National Science Foundation (NSF). This research project is also funded in part by the NSF Research Experiences for Undergraduates grant and by the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program. Existing bathymetry from a previous project, the Keystone Harbor of Whidbey Island of the Puget Sound of Washington was slightly modified and used as the inundation zone for the tsunamis. The scale of the experiment is approximately 1:40 as documented by the Keystone Harbor research study. This bathymetry was used because it represents a complex variation of high bluff, embayment, and low foreshore regions which may be affected by tsunami waves.

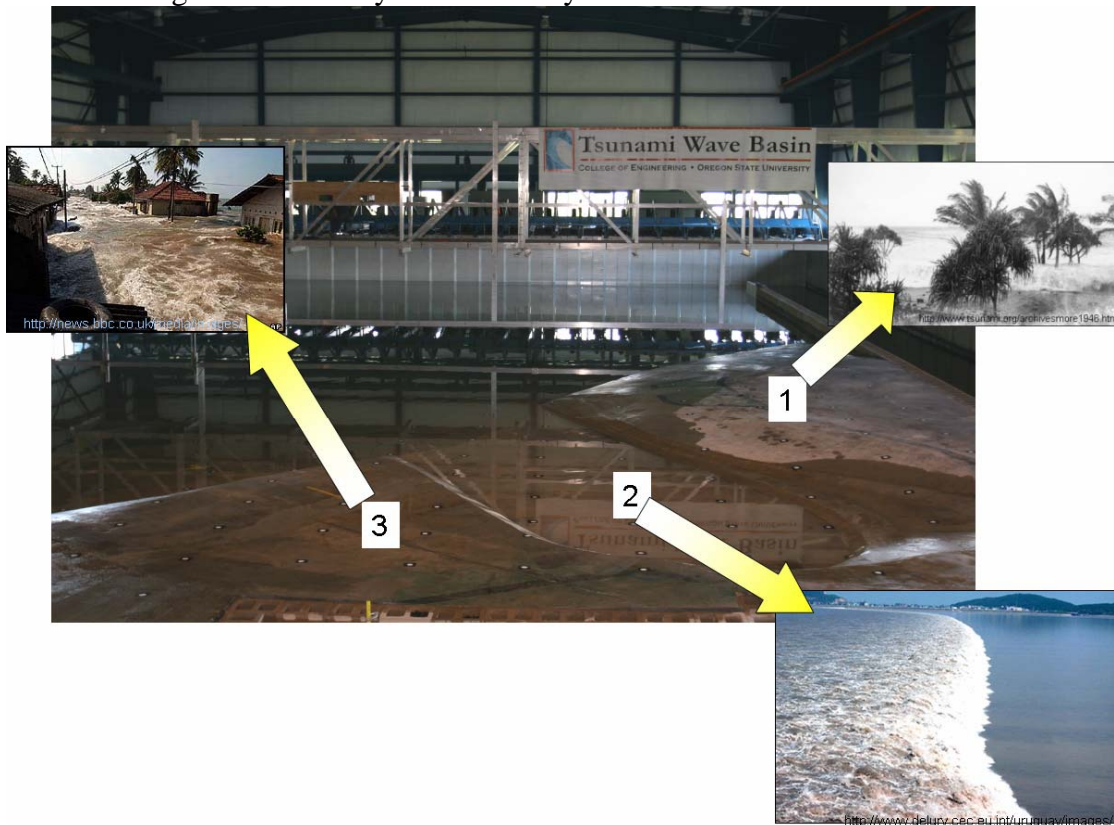


Figure 1. Overview of experimental bathymetry.
Insets: 1. High bluff. 2. Embayment area. 3. Low foreshore.

Proposed parameters to be included in the benchmark data set are onshore and near-offshore water velocity, wave height, and impact pressure. As part of the shared-use concept of the National Science Foundation's Network for the Earthquake Engineering Simulation program, this data set will be used for numerical model verification and lead to better overall understanding of tsunamis.

3. Experimental Setup

3.1 Basin Preparation

A cinderblock wall, sloped wooden and metal wedge, and section of concrete bathymetry were added in the southeast portion of the basin to account for smooth transition of waves from the wave maker to the inundation bathymetry. The 48.8m long by 26.5m by 1.0m depth capacity basin and bathymetry were originally surveyed with a LIDAR survey system producing a 3D grid of $>10^6$ points. The concrete addition to the bathymetry was surveyed in manually with a Nikon Pulse Laser total station and survey rod. These additional survey points were then integrated into the LIDAR survey data. A one meter by one meter grid system was measured painted in using existing benchmarks, surveying tape, and laser levels in order to create a reference grid for onshore velocity data collection. Final preparations of the basin included the draining and cleaning of the basin and removing stones that were washed into the basin from previous experiments.

3.2 Instrumentation Setup

Instruments used in the experiment were: a) four acoustic-Doppler velocimeters (ADV) for collection of near off-shore and harbor velocities, b) four capacitance wave gages for collection of wave heights, c) one Particle Image Velocimetry (PIV) camera for onshore velocities, and d) three to five pressure inducer sensors to measure impact pressure. At the present time, only ADV and wave gage data collections have been completed. A mobile bridge running north to south, moving east and west, was utilized for instrument and computer placement. The acoustic-Doppler velocimeters and co-located capacitance gages were mounted to an I-beam which was attached to the bridge.



Figure 2. Instrument array on I-beam.

Insets: Top left. Capacitance wave gage. Bottom right. Acoustic-Doppler Velocimeter.

Four different wave types (two at 55 centimeter water depth and two at 44 centimeter water depth) were ran using the serpentine wave maker with 29 independent paddles and maximum stroke capabilities of 2.1 meters at 2.0 meters per second. Table 1 displays wave types.

Table 1. Wave case type and descriptive parameters.

Case	Depth (cm)	Wave Condition	H (cm)	Description
1	55.0	Soliton	25.0	Wave breaking and overtopping
2	55.0	Soliton	5.0	No breaking, minor overtopping
3	44.0	User Defined	5.0	90% stroke of wave maker, some breaking in channel, minor overtopping
4	44.0	Soliton	5.0	Some breaking, no overtopping

4. Procedure

4.1 Point Conditions

Water depth was held at 55 centimeters and wave Case 1 and 2 were run at 25 different X and Y locations on a previously decided testing grid. Three regions tested were the North side of the basin, South side of the basin, and the Harbor. At a depth of 44 centimeters, wave Cases 3 and 4 were ran at 19 different X and Y locations. Two regions were tested, North and South sides of the basin. Water depth was measured to the nearest millimeter of accuracy before location trials began. Four ADVs and wave gages were used for each of the 88 runs unless water depth or bathymetry limited placement. In those instances, instruments were removed, disconnected, or moved to another location. Refer to Figure 3 for complete grids.

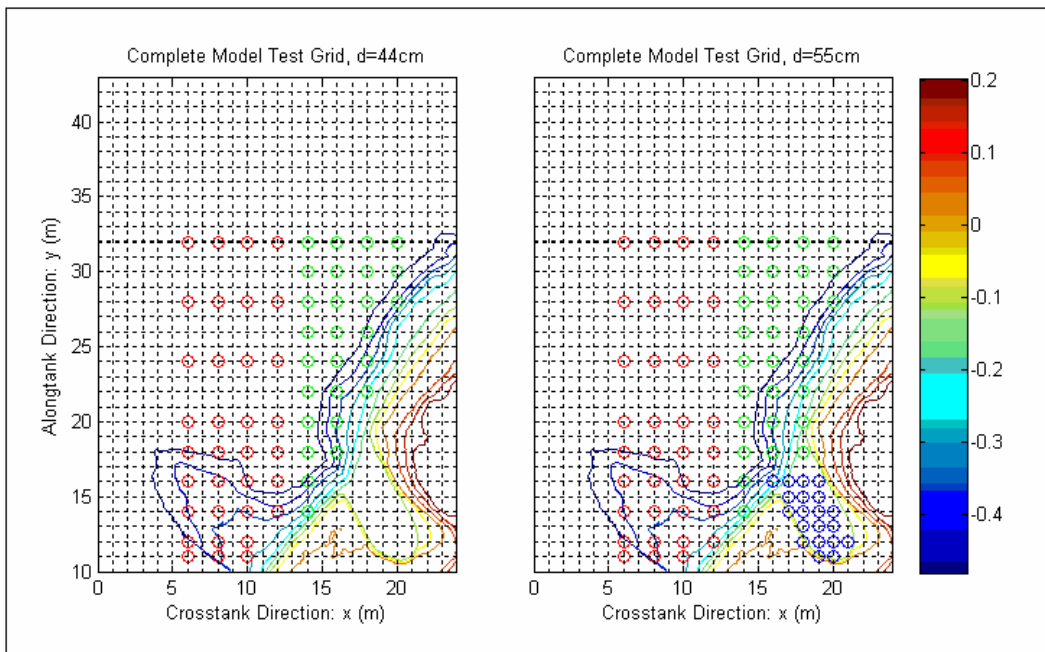


Figure 3. Complete testing grid for 44cm (left) and 55cm (right) water depth conditions.

4.2 Data Acquisition

Total run time was 12 minutes. Actual data acquisition was the first two minutes of the run. The last 10 minutes were allotted for the water in basin to return to ambient still water conditions. The 10 minute period was also used to reset the wave maker, change wave types, move the bridge, and save previously collected. Each side of the bridge, north and south, was measured for accuracy by ruler each time the bridge was moved. The bridge was measured to the nearest millimeter to the east or west of previously measured meter increment marks that served as general location reference.

The ADVs and wave gages were synchronized to take data simultaneously; however, the wave maker ran separately. Portable handheld bi-directional radio transceivers were used to communicate between the bridge and the wave maker. It is noted that wave cases 1, 2, and 4 acquired key parameter data between 20 and 40 seconds of the 2 minute acquisition period. Case 3 acquired the key parameter data between 40 and 80 seconds of the 2 minute acquisition phase. Key parameters to be considered are maximum wave height and maximum wave velocities in three dimensions.

5. Preliminary Data

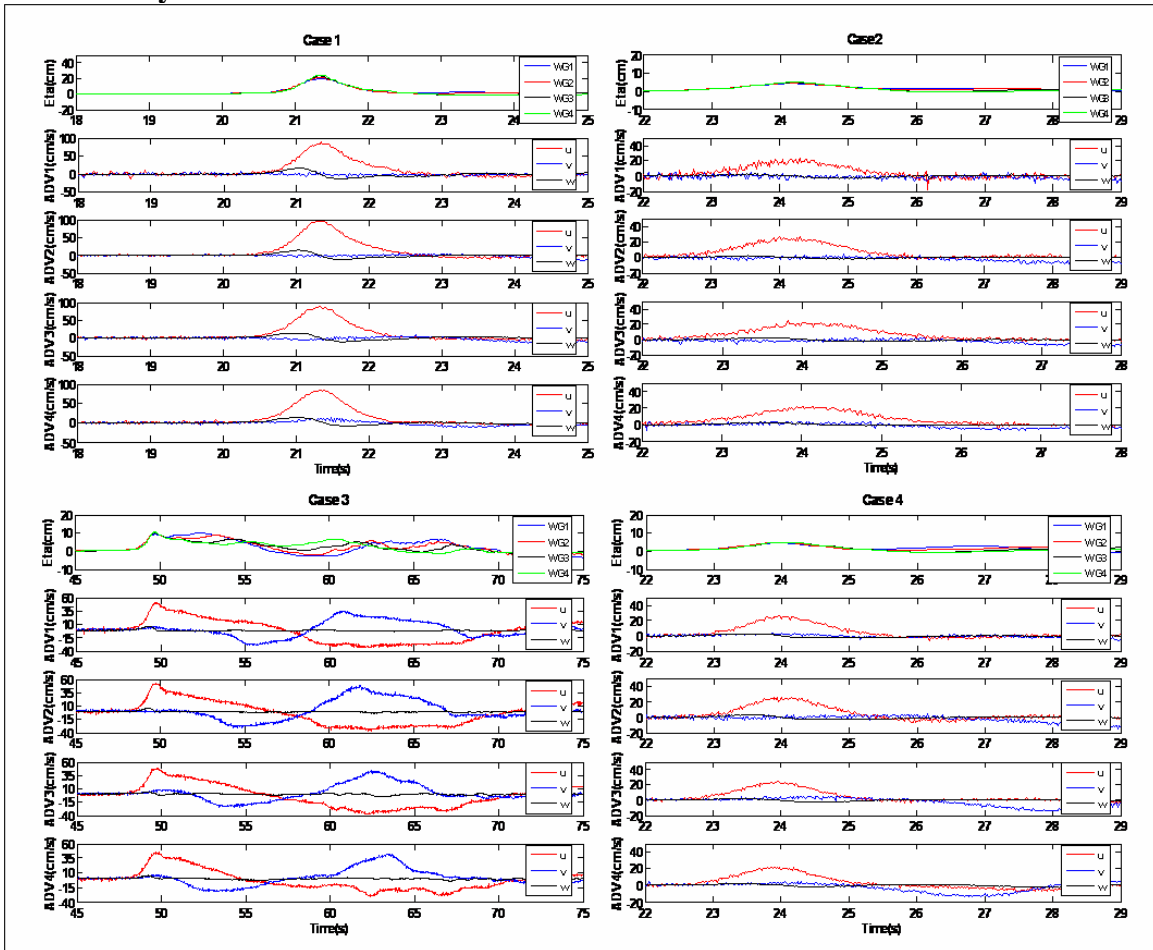


Figure 4. Preliminary time series plots. Cases 1 through 4 are represented with five time series plots. In descending order: wave gage wave heights 1 through 4, ADV 1, ADV 2, ADV 3, and ADV 4.

Preliminary data were gathered using National Instruments LabVIEW 7.1 wave gage collection and SonTek/YSI Sontek Horizon ADV 1.04 acoustic-Doppler velocimeter collection software. A total of 168 data points were collected for Case 1 and 2 conditions in the north, south, and harbor regions of the bathymetry at the 55cm still water depth. At the 44cm water depth 120 data points were collected for Case 3 and 4 conditions. Figure 4 illustrates a comparison of the raw data time series plot of the four wave type conditions located in the north region. Different wave heights and velocities are observed for each location. A master data log containing the raw data time series plots for all X,Y locations was compiled.

When reviewing compiled data, it should be noted that the full data collection timeframe, one minute for Cases 1 and 2 and two minutes for Cases 3 and 4, is displayed. Any comments about problems with data acquisition or compilation are also included. As with any experimental study, problems occur. However, with extensive review of theory compared to laboratory simulated data, these problems can be noted and accounted for.

6. Preliminary Results

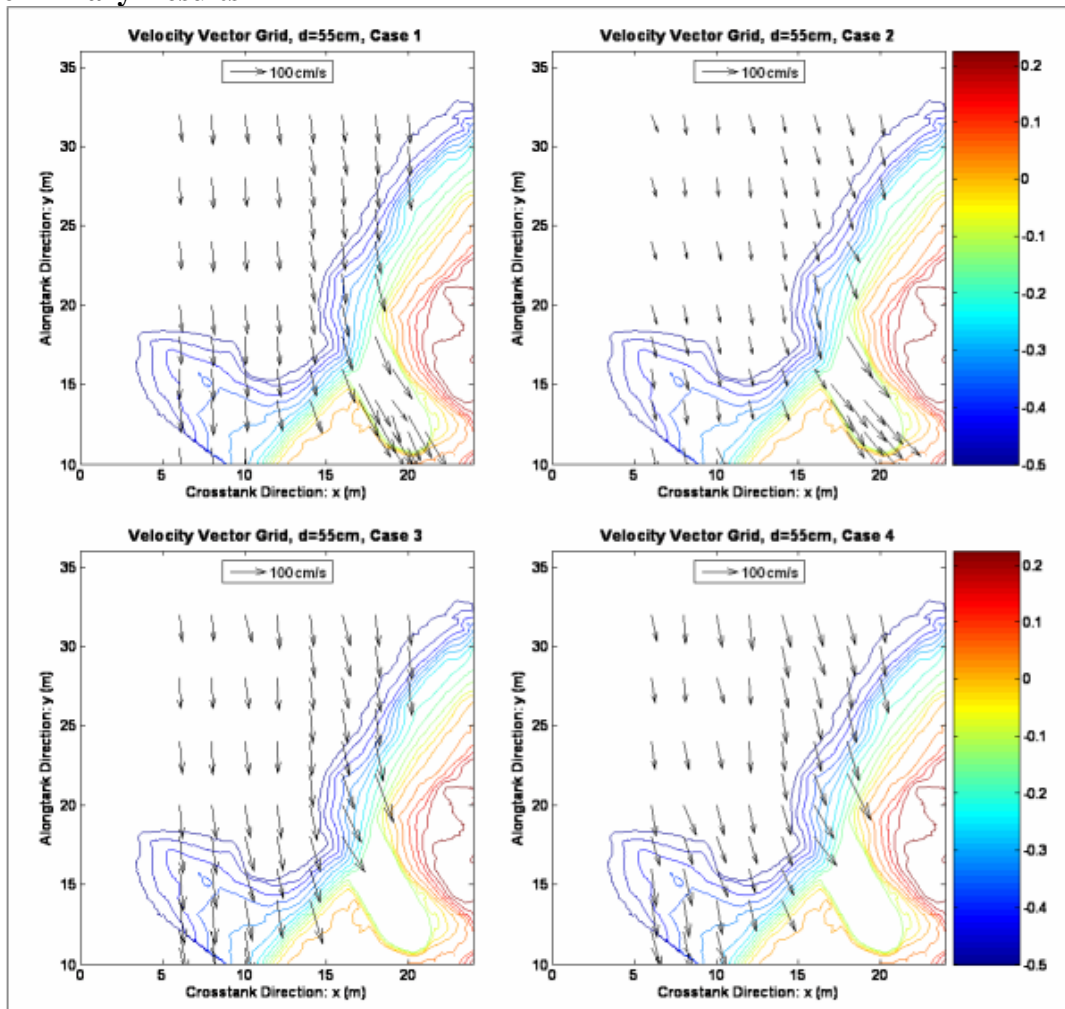


Figure 5. Preliminary maximum horizontal velocity vector grids. Cases 1 and 2 at 55cm water depth and Cases 3 and 4 at 44cm water depth are presented for comparison.

As expected with long wave run-up theory, velocity vectors increase as water depth decreases. Three dimensional flow is observed as the data point locations reach the shoreline (Figure 5). Case 1 and 2 maximum horizontal velocity vector flow is presented for the north, south, and harbor regions of the basin. Case 3 and 4 maximum horizontal velocity vector flow is presented for the north and south regions. Of particular note is the harbor section, where flow magnitude is largest and directed towards the southwest part of the basin. Because the tsunami waves are striking the bathymetry at an angle as opposed to straight on, the complexity is increased and becomes more realistic to tsunami field conditions.

7. Discussion

Two wave characteristics are presented, wave height and near shore wave velocity. It was discovered that the clearness of the water presented problems for ADV instruments. Because ADV instruments rely on sound Doppler signals, essentially noise to sound ratios, water clearness creates wide scatter because even minute sounds are registered. To compensate for this problem, neutrally buoyant glass micro-particles were added to the water in a concentration of 43.8 mg/L. Serving as a seeding material, the micro-particles eliminate wide scatter readings for ADV instrumentation (Figure 6).



Figure 6. Water with glass micro particle seeding material.

Difficulties also arise when measuring shallow depth wave velocity with ADV instrumentation. Shallow water depths present the difficulty of instruments becoming un-submerged from the water. When this occurs, large sound wave spikes occur and distort data. While these distortions can be accounted for, future collection methods aim to overcome these problems through the use of the alternate instrumentation.

7.1 Future Work and Conclusions

For additional data collection, a particle image velocimeter (PIV) camera is currently being implemented to measure shallow water depth and onshore wave velocity.

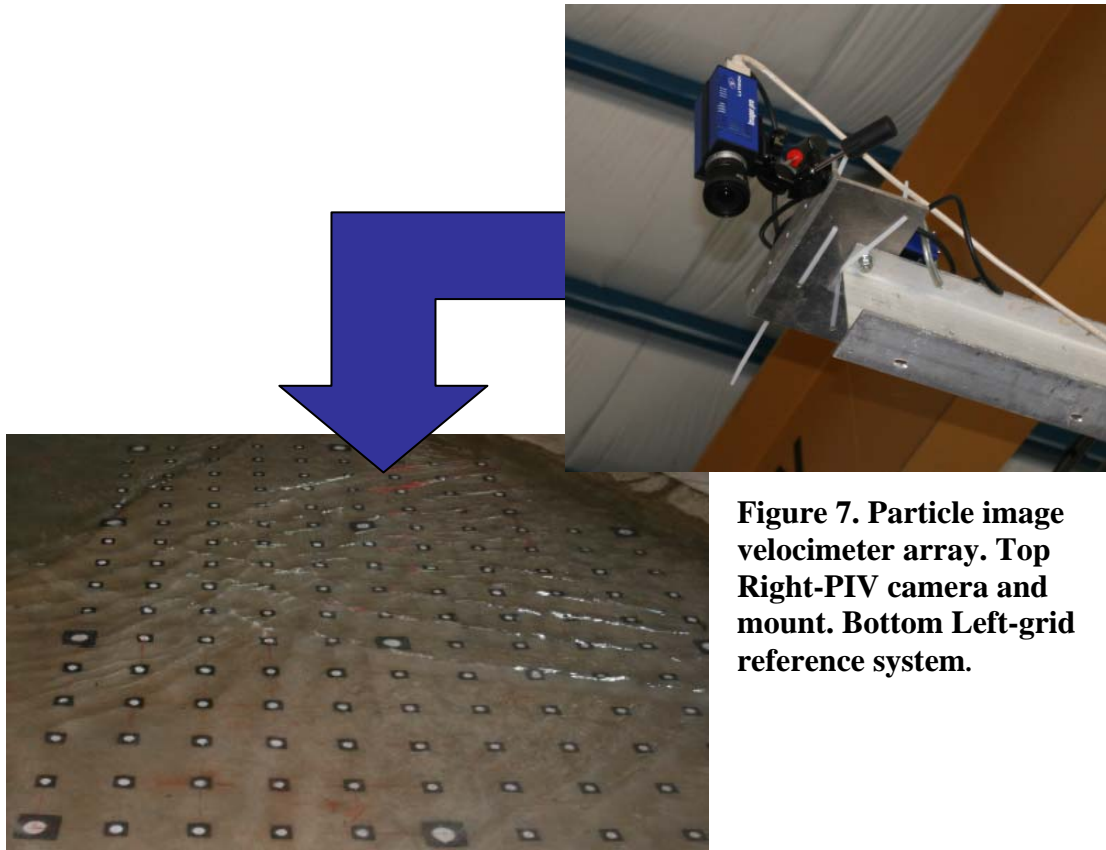


Figure 7. Particle image velocimeter array. Top Right-PIV camera and mount. Bottom Left-grid reference system.

Figure 7 illustrates the current PIV data collection system. The camera is mounted to an I-beam attached to the top of the mobile bridge and records data directly below it. A grid system with major markings every meter and minor markings every twenty centimeters was painted onto the bathymetry to allow for PIV reference and orientation of data. A pressure transducer array, consisting of 3-5 pressure transducers arranged in a cylindrical casing will be deployed to collect wave pressure impact parameters. With additional analysis and data organization, a comprehensive three dimensional data set over a complex bathymetry will be completed and made available on the George E. Brown Jr. Network for Earthquake Engineering Simulation online information database for scientific use in numerical modeling, furthering tsunami inundation understanding.

8. References

¹Briggs, M.J., Synolakis, C.E., Harkins, G.S., and Green, D.R. (1995). "Runup of solitary waves on a circular island." *Long-Wave Runup Models*. 363-374.

²Briggs, M.J., Synolakis, C.E., Harkis, G.S., and Hughes, S.T. (1995). "Large scale three-dimensional laboratory measurements of tsunami inundation." *Tsunami: Progress in Prediction, Disaster Prevention and Warning*, 129-149.

³Hamzah, M.A., Mase, H., and Takayama, T. (2000). "Simulation and experiment of hydrodynamic pressure on a tsunami barrier." *Coast. Engrg.*, 1501-1507.

⁴Liu, P. L.-F., Synolakis, C.E., and Yeh, H.H. (1991). "Report on the international workshop on long-wave run-up." *J. Fluid. Mech.*, 229, 675-688.

⁵Titov, V.V., and Synolakis, C.E. (1998) "Numerical modeling of tidal wave runup." *J. Wtrwy. Port Coast. and Oc. Engrg.*, 124(4), 157-171.

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Please see <http://wave.oregonstate.edu/> for additional information about the O.H. Hinsdale Wave Research Laboratory.

10. Brief Bio

My name is James Lynch. I am from Forreston, Illinois and attending the University of Wisconsin at Platteville. Majoring in environmental engineering, I plan to attend graduate school for environmental and energy engineering management. Future ambitions include work in the government sector, possibly for the Environmental Protection Agency or other federal organization. This is my second summer of participation in the Research Experiences for Undergraduates program. In the summer of 2004 I worked under Dr. William Riddell at Rowan University in Glassboro, NJ in an REU themed for pollution prevention and sustainable development. My sole published work is a co-authorship entitled from that REU with the following reference: "A Markov chain model for fatigue crack growth, inspection and repair: The relationship between probability of detection, reliability and number of repairs in fleets of railroad tank cars" W.T. Riddell, J. Lynch, Paper PVP2005-71671 in Proceedings of PVP2005, 2005 ASME Pressure Vessels and Piping Division Conference, Denver, CO, July 17-21, 2005. The REU program funded by the National Science Foundation has been rewarding and a true insight into the time and effort involved with graduate studies. Along with the work there have also been many great life experiences that have ultimately shaped my path and career ambitions. I would like to close with a thank you to the NSF and the individuals that I have participated with in the REU program.