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Experimental Simulation of Tsunami Hazards to Buildings and Bridges

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Abstract: This project investigates tsunami hazards faced by coastal infrastructure through experimental and numerical simulation. Primary focus of the investigation is on scour and fluid loads from run-up, inundation, and drawdown when tsunami bores hit structures. The focus of the experiments is to obtain quality data that can be used to validate numerical models and codes. The objective of this paper is to document the complete experimental set-ups as well as the sequence of experiments and to provide some preliminary data. The paper will provide a reference of the experimental design that subsequent publications can cite.

1. Introduction: Coastal infrastructure such as buildings, bridges, highways, and harbor facilities near shorelines that are susceptible to tsunami inundation are at risk of significant damage if the structures are not adequately designed for such loads. The 2004 Great Indian Ocean Tsunami demonstrated this, and the devastation has been well-documented. Ref. [1-3] show clear examples of damage as a result of both scour and fluid loading from that tsunami. The structural damage is very similar to what can happen from hurricane storm surge and waves. Such damage from Hurricane Katrina is shown in Figure 1–Figure 3.

Figure 1. US-90 bridge from Bay St. Louis to Pass Christian showing dislocation due to buoyancy and hydrodynamic loads [4]

Figure 2. Double-tee negative bending failure in parking structure at Grand Casino, Biloxi – bottom picture is inset from top picture [5]

Although there are some clear differences between the damage mechanisms of tsunami and hurricane surge/waves, there are also similarities and the resulting damage is strikingly similar.

The tsunami threat has been receiving increased attention. A recent special issue of the ASCE *Journal of Waterway, Port, Coastal and Ocean Engineering* focused on tsunami engineering, which was defined as 'those activities that are significant for the engineering goal of designing and protecting the built environment and the people that dwell therein, with regard to potential tsunami hazards' [6]. Unfortunately, designers of onshore facilities typically have very little experience and receive very little guidance in tsunami induced loads that should be considered for bridge and building design [7, 8]. In addition, the estimation of these loads numerically, through simulation software, is very complex, and requires sophisticated computational fluid dynamic models and sediment transport and scour models.

Figure 3. Scour failure of Beach Boulevard in Bay St. Louis [5]

The current project is titled 'Development of Performance-Based Tsunami Engineering, PBTE', and its goal is to develop the methodology and validated simulation tools for implementation of site specific PBTE for use in the analysis, evaluation, design and retrofit of coastal structures and facilities, as well as the development of code-compatible provisions for tsunami resistant structural design. The project focuses on the following physical hazards as a result of tsunamis hitting a coastline: 1) run-up and inundation, including fluid velocities and energy dissipation; 2) fluid loading on structural elements; and 3) sediment transport and scour as a result of inundation and drawdown. The project has both experimental and numerical components.

As mentioned, the simulation of tsunami hazards requires complex numerical models. These models require significant validation with experimental data, and the experimental component of the project has been designed to deliver data for model validation. Many previous experiments either have not been of sufficient scale or have not focused on required data for important scenarios [9, 10]. For example, very little experimental data has been obtained for the case of a fringing reef, which can affect the tsunami bore formation and subsequent coastal inundation. As a result, this project involves an experimental component of sufficient scale that involves tsunami bores propagating over a fringing reef. In addition to fringing reefs, there has also been very little study of tsunami sediment transport and scour. Although tsunamis have been known to mobilize substantial amount of sediment deposits, [11, 12] represent the only published experimental work known to the authors on the subject of tsunami scour. However, neither study collected enough data to develop a sediment transport model to predict tsunami scour. Hence, one of the goals of this project is to improve the understanding of the dynamics of tsunami sediment transport and scour via experimental and numerical modeling.

Experiments are being carried out that focus on 1) run-up/inundation including the effect of energy dissipation; 2) structural loading; and 3) sediment transport and scour. A primary focus of the experiments for run-up and inundation is the energy dissipation over the fringing reef, which has a substantial impact on the run-up, inundation, and fluid velocities to which coastal infrastructure will be subjected. The structural loading experiments are designed to determine fluid loads on a number of different structural configurations, primarily components such as columns, walls, decks, and relevant combinations of these. A major interest is correlating the force magnitude and location with bore shape and speed, and obtaining sufficient fluid data, such as velocity, to validate CFD models. The sediment transport and scour experiments are designed to study tsunami erosion and deposition processes, including the effects of wave shapes, wave-soil interactions, and wave-soil-structure interactions. The goal is to collect benchmark data for development and validation of tsunami sediment transport models, and ultimately to develop design tools to predict the scale and location of tsunami scour.

The project's experimental design and test matrix are described in detail herein. The objective is to describe the complete experimental program to provide a reference that can be cited in subsequent, more focused publications. The experiments are on-going, as is the data analysis. However, some preliminary results are also reported herein.

The experimental set-ups for each of the three thrusts (run-up/inundation; structural loading; and sediment transport and scour) of the experimental program will be described separately. First, however, a general description of the experimental facilities and the basic set-up common to all three thrusts will be described.

2. Basic Experimental Setup: The experiments are being conducted at the O.H. Hinsdale Wave Research Laboratory of Oregon State University (OSU). The specific facility is the Tsunami Wave Basin (TWB), which is an NSF NEES facility. The rectangular basin (Figure 4) is 48.8 m x 26.5 m x 2.1 m. The maximum water depth is 1.3 m, resulting in a freeboard of 0.8 m.

The wavemaker is a piston-type, electric motor. It consists of 29 boards, each 2.0 m high. Regular, irregular, and tsunami (solitary) waves can be generated, both single and multi-directional. The wave periods range from 0.5 s to 10 s. The pistons have a maximum stroke of 2.1 m and a maximum velocity of 2.0 m/s. Information on the facility can be found on the web [13].

Unfortunately, the TWB does not have a reconfigurable beach, and beach configurations for specific projects must be custom made. For our experiments, we required a number of beach slopes and fringing reef configurations. It would have been too expensive, and taken too long, to reconfigure beaches that spanned the entire 26.5 m width of the basin. In addition, to obtain the data required, we were mostly interested in two-dimensional flow. As a result, we constructed two concrete walls along the length of the basin to create three channels, two of which are 2.16 m wide and are used in our experiments (Figure 5). The outer wall has three 1.1 m x 0.7 m Plexiglas viewports downstream to obtain a vertical plane view and video capture of the fluid flow and sediment transport. The remainder of the basin, approximately 21.8 m wide, is used by OSU for unrelated tsunami experiments and for a payload project. All three channels experienced the same wave fields, which were controlled by our tests.

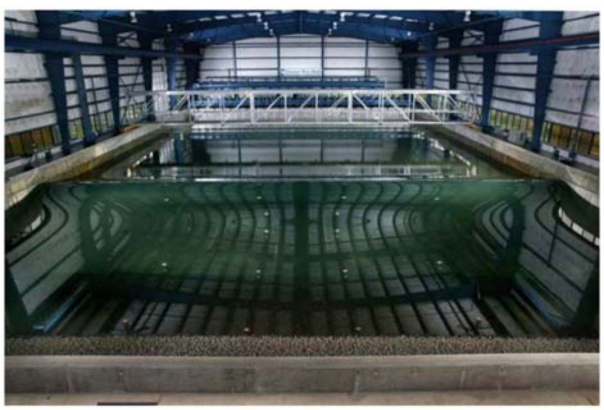

Figure 4. Tsunami Wave Basin (TWB) [13]

Our experiments required five sets of basic beach configurations: two with a constant slope from the bottom of the basin at slopes of 1:10 and 1:15, and three with beach slopes of 1:5, 1:10, and 1:15 and a fringing reef. In the cases of a fringing reef, the beach slope terminated at an elevation of 1 m above the basin bottom and was horizontal thereafter. The basic configuration is shown in Figure 6 for the 1:10 beach slope with reef. For the run-up/inundation studies and the structural loading studies, the beach was concrete (except for the 1:15 slope, the upper portion of which was a steel plate). For the scour studies, the slope was created by sand. Water depths of 1.0, 1.05, 1.10, and 1.15 m were used. Wave heights from 0.1 to 0.6 m in increments of 0.1 m were used. While the focus was on solitary waves, to model a tsunami, some cnoidal and storm waves were also run to obtain a broader range of data.

Figure 5. Channels installed in TWB

In the following sections, the experimental setups and results from each of the three thrusts are discussed in more detail.

3. Wave Energy Dissipation: The coastlines around Hawaii and other tropical locations are fronted by fringing reefs, which typically consist of a steep reef face and a shallow reef top with highly irregular surface. These large coastal features between land and ocean may have significant implication for tsunami hazards assessment and mitigation. Apart from anecdotal reports of tsunami damage or lack of damage to coastlines with reef structures, a systematic study of the protection provided by fringing reefs to coastal infrastructure is not immediately evident.

Five series of experiments were specifically designed to investigate tsunami transformation and energy dissipation over fringing reefs. The two constant-slope experiments are primarily used to test the effects of bedform roughness on tsunami bore formation and energy dissipation. The three reef configurations were designed to cover natural fringing reef profiles gathered from Oahu, Hawaii and Guam, Mariana Islands. For some of the tests, a reef crest is added at the reef edge to create a shallow lagoon behind.

Figure 6 shows, for example, the experimental setup for the 1:10 reef configuration. A resistance wave gauge near the wave maker records the incident wave profile, while gauges placed at 1 m intervals over the reef face record the profile transformation. The formation of the bores at the reef edge and the corresponding velocity profile are captured by four ADVs mounted from a bridge across the flume. A series of pressure transducers record the transformation of the bore over the reef top. The recorded data will be used to calibrate tsunami inundation models that may be used in PBTE (e.g., [14, 15]). A breaking bore is shown in Figure 7.

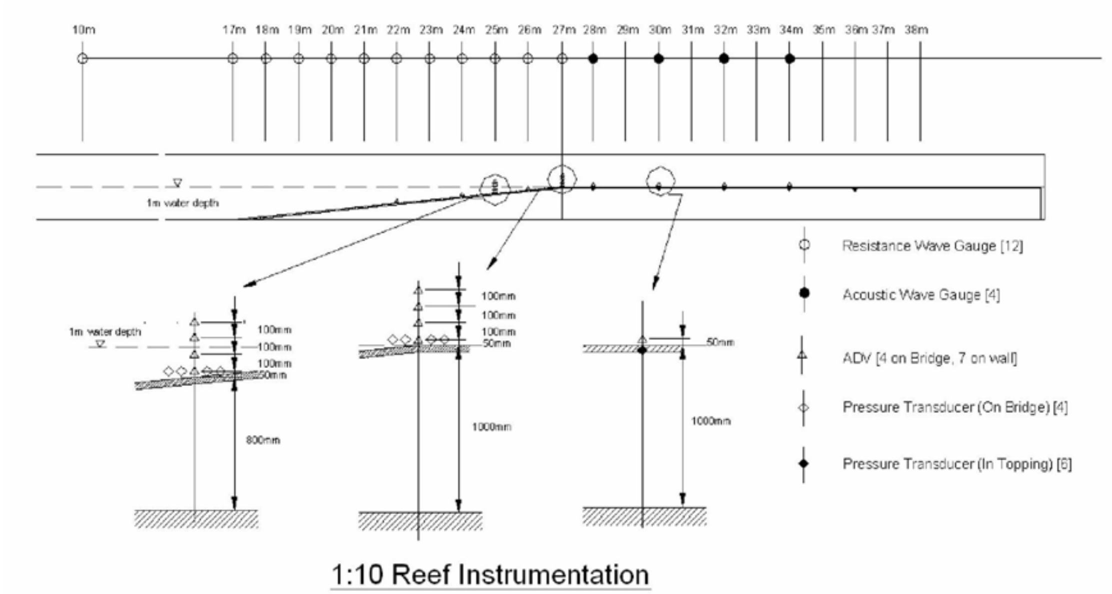

Figure 6 Beach slope and basic instrumentation for tsunami dissipation study

Figure 7 Breaking bore

4. Structural Loading: The structural loading experiments were designed to determine the loading time-history imparted on various structural elements by a tsunami bore. The experiments were performed on the flat reef portion of the wave channels. Soliton wave heights of 0.2, 0.4 and 0.6 m were used for the structural tests. The incoming soliton transforms to a turbulent bore at the transition between the beach slope and the fringing reef. This bore then impinges the structural test specimen. Immediately prior to impact, the bore shape and velocity were recorded by a laser surface profiler, LSP. The LSP involved filming the water surface reflection of a vertical laser sheet oriented along the centerline of the wave channel. A typical LSP capture of a bore leading edge is shown in Figure 8, which also shows the run-up of the bore on the front of the test specimen, located at a distance of 110 cm in the figure. The gray vertical bars indicate the location of the specimen. In the figure, the zeroes for time and distance in the figure are taken arbitrarily, while the height is from the bed.

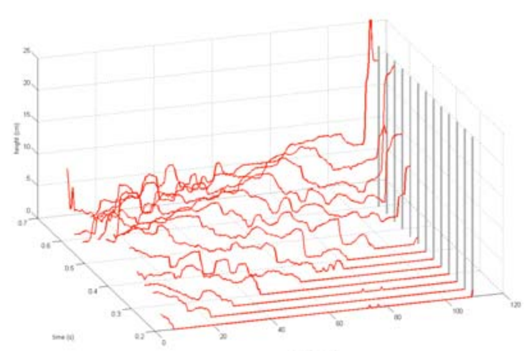

Figure 8. Laser surface profile of advancing bore

The structural elements tested in this study represent portions of a prototype multistory building. Testing involved individual square columns with dimensions of 50.8 mm (2 in) and 101.6 mm (4 in), and rectangular columns with dimensions of 152.4 mm x 50.8 mm (6 x 2 in) and 304.8 mm x 50.8 mm (12 x 2 in), with the wide side facing the incoming bore. These columns also were tested in a configuration of three identical columns spaced 0.71 m on center across the wave channel, representing a perforated wall with various degrees of opening. A solid wall across the wave channel was also tested (Figure 9).

Each column specimen was supported by two load cells connected to a braced support post (Figure 10). The upper load cell was a pin ended uniaxial force sensor, while the lower load cell is a 6-degree of freedom force and moment sensor. These are the only support points for the test specimen, allowing for computation of the resultant horizontal force on the specimen and the location of application of this force. Figure 11 shows a typical force time-history for a column specimen.

The individual square and rectangular columns were tested in a shielded configuration representing an interior column or wall element in the prototype building. By locating the instrumented column behind each of the perforated walls described previously, different degrees of shielding were achieved. The instrumented column was located both in line with a leading column, and centered between two leading columns to study both the shielding and flow concentration effects of a bore passing through a row of columns or perforated wall (Figure 12).

To measure the vertical forces on a typical floor slab in a multistory building, a horizontal plate specimen was supported at various heights above the channel bottom and subjected to tsunami bores from 0.2, 0.4 and 0.6 m solitons. The same load cells were used to record the vertical load time-history and its location on the plate. Pressure sensors on the bottom surface of the plate were used to record the pressure distribution along the centerline of the plate from leading to trailing edge. The plate specimen also was located immediately in front of the perforated wall elements described previously. This simulates a typical floor slab supported by columns or wall elements. Finally, the plate specimen was tested with a solid wall along its downstream edge.

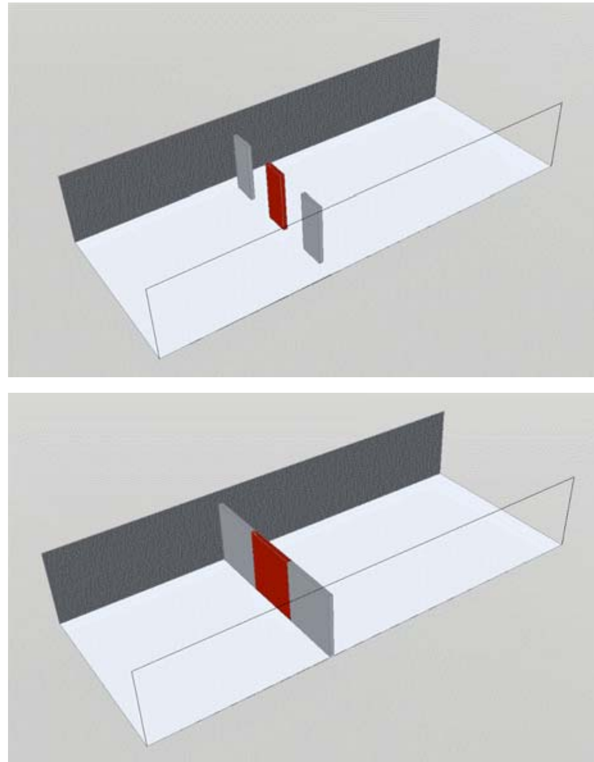

Figure 9. Perforated and solid wall configurations (Center segment instrumented).

Figure 10. Column specimen (101.6 mm square) supported by two load cells and reaction frame. Isometric rear view (left) and front view (right).

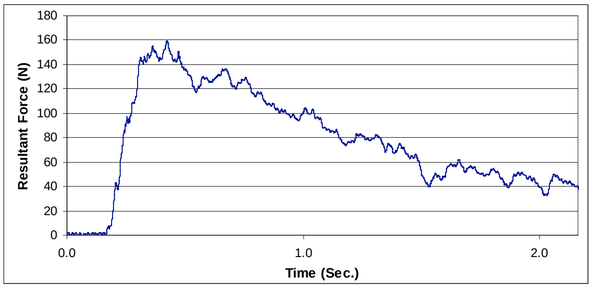

Figure 11. Force time-history for a typical column specimen.

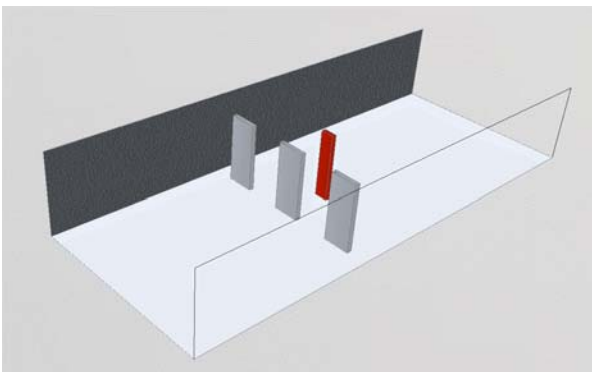

Figure 12. Instrumented column located behind leading row of columns.

5. Scour/sediment Transport: This set of experiments was designed specifically to study tsunami-induced bed erosion, deposition, and sediment transport. The flume was heavily instrumented to measure the wave surface elevations, sediment concentration, near bed flow velocity, fluid pressure, soil pore pressure, and bed profile changes. Underwater videos were also used behind the Plexiglas windows to visualize the sediment transport processes near shore. Natural Oregon beach dune sand was used in the experiment. The median grain diameter, uniformity coefficient, hydraulic conductivity, and grain fall velocity are 0.21 mm, 1.67, 26 μm/s, and 2.9 cm/s, respectively. The soil porosity is estimated to be 0.39. A photograph of the instrumented flume is shown in Figure 13. Details of the experimental setup are presented in [16, 17].Three different bed configurations were used in this experiment: constant 1:10 slope (M10), 1:10 slope with a flat reef (RF10), and constant 1:15 slope (M15). In addition, a cylinder was installed on the flat portion of the bed for the RF10 case, which is considered as the fourth bed configuration, CY10, although the bed was the same as in RF10. The nominal water depth was 1m for M10 and M15, and 1.1 m for RF10 and CY10. Solitary waves and cnoidal waves of different wave heights were examined for the different bed configurations. The specific wave conditions tested on each bed configuration are summarized in Figure 14.

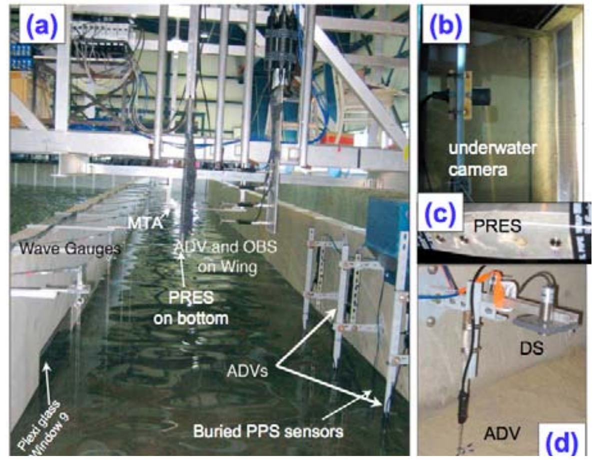

Figure 13 Photograph of the instrumented flume for the tsunami scour experiment. (a): The flume with wave gauges, acoustic Doppler velocimeters (ADVs), buried pore pressure sensors (PPSs), Plexiglas windows, and the bridge (where the multiple transducer array (MTA) and wings are mounted) in place. The details of the wings with the optical back scatter sensors (OBSs), ADVs, and pressure transducers (PRESs) can also be seen from this figure. (b): Top view of an underwater camera mounted inside the box behind one of the Plexiglas windows. (c): Pressure transducers mounted at the bottom of the left wing unit shown in (a). (d): Detailed view of one of the ADV and distance sonic mounted to measure the flow velocity and wave profile onshore. Taken from [16].

An example of the measured initial wave profile for a 50 cm solitary wave, and the changes in bed profile due to 3 (trial 3), 6 (trial 6), and 9 (trial 9) 50 cm solitary waves over a 1:15 slope are shown in Figure 15. The same plots for 50 cm cnoidal waves are shown in Figure 16. The results indicate that solitary waves lead to erosion above the shoreline (x=27m) and deposition in the breaking region. The maximum scour per 50 cm solitary wave was approximately 4 cm. Cnoidal waves, on the other hand, lead to erosion in the wave breaking region, and deposition immediately above the shoreline and seaward of the wave breaking region. The maximum erosion and deposition were also significantly less for the cnoidal waves due to wave-wave interactions, which significantly changed the runup and drawdown characteristics. The maximum scour per 50 cm cnoidal wave was approximately 0.7 cm. Equilibrium bed profile was not reached even after nine waves for all cases. The results indicate that tsunamis can erode substantial amount of sand, and the erosion and deposition patterns are highly influenced by the wave type and bathymetry.

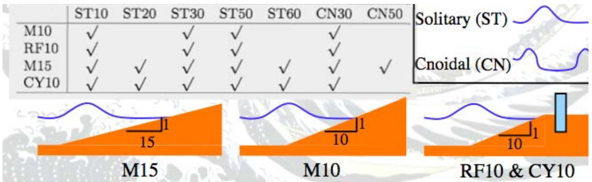

Figure 14: Schematic table and drawing of the different wave conditions and bed profiles examined in the tsunami scour experiment. In the table, ST and CN denote the solitary and cnoidal wave respectively, followed by the wave heights in centimeters.

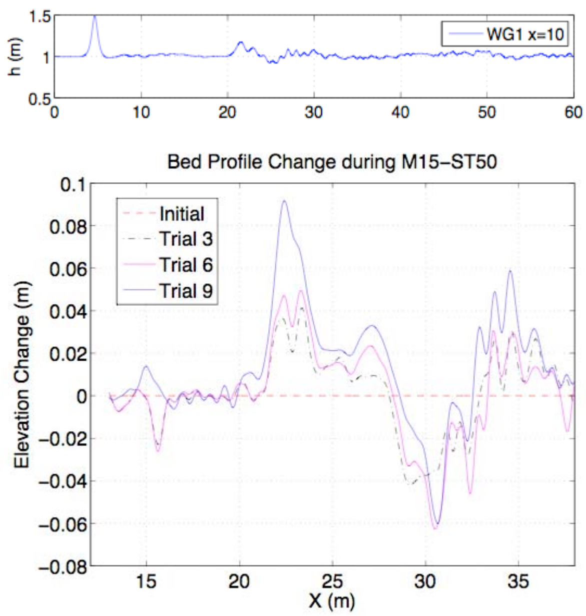

Figure 15: Measured initial wave profiles for a 50cm solitary wave, and the changes in bed profile due to 3 (trial 3), 6 (trial 6), and 9 (trial 9) 50 cm solitary waves over a 1:15 slope.

6. Conclusions: Fluid loads and sediment transport and scour from tsunami inundation and runup can pose a significant risk to coastal infrastructure. To develop a rational design capability for these risks will require state-of-the-art simulation. These models are complex and require significant validation with experimental data. However, adequate data are lacking. The present project is obtaining additional data at the experimental scale that can be used to validate the models. The models will then be able to be used to determine the risks of the prototype infrastructure with more confidence. Although not discussed herein, from the experimental and numerical results the project will also develop code-compatible provisions to help designers provide tsunami-resistant structures.

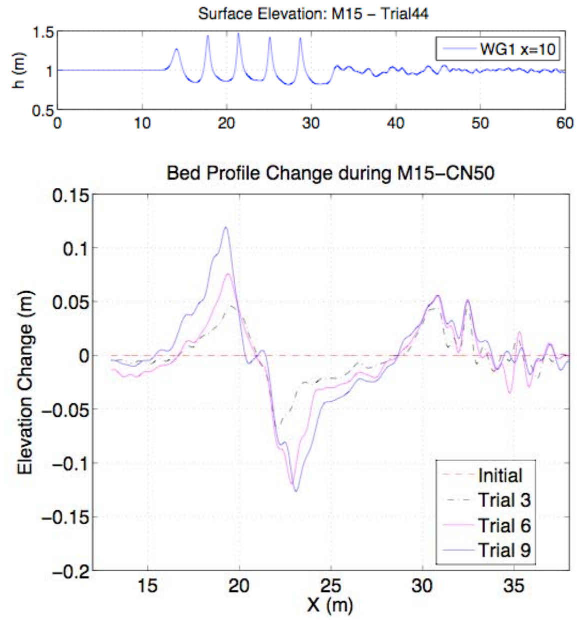

Figure 16: Measured initial wave profiles for a 50cm cnoidal wave, and the changes in bed profile due to 3 (trial 3), 6 (trial 6), and 9 (trial 9) 50 cm cnoidal waves over a 1:15 slope.

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