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DEVELOPMENT OF AN APPARATUS FOR THE SIMULATION OF COASTAL STRUCTURES SUBJECTED TO TSUNAMI

Liam JONES[1] , Ioannis ANASTASOPOULOS[2]

ABSTRACT

The protection of coastal or near-water infrastructure from tsunami events is a critical issue for many seismically active regions. The interaction between tsunamis and marine infrastructure is a complex and difficult problem that combines aspects of hydraulics, geotechnical and structural engineering. Designing effective mitigation measures and strategies requires deeper understanding of critical failure mechanisms, key to which is realistic experimental and numerical modelling. For this purpose, this paper presents the design of a novel apparatus that can experimentally capture both the structural-geotechnical and fluid-mechanical aspects of the problem, from which predictions of the performance of real structures can be made. The final aim being to provide realistic and practical design strategies for coastal structures, as well as behavior predictions for existing vulnerable structures. The tsunami is generated by means of a miniature tidal generator, controlled by air pressure, which has been shown by previous studies to be an effective lab-scale approximation of a real Tsunami. 1g tests are conducted in order to calibrate the apparatus and design an efficient experimental setup. Additionally, optimum data collection set-ups are to be investigated, along with identification of critical mechanisms and interactions worthy of further, more focused, study. Data and observations from 1g tests will then be used to further the ultimate aim of the project: to modify a drum centrifuge such that a gravity scaled soil-structure system is subjected to a pressure-controlled tsunami wave, whose physical and geometric properties can be precisely controlled. The paper discusses the key aspects of design of such an experimental procedure and apparatus.

Keywords: Physical Modelling, Tsunami Simulation, Novel Experimental Technique, Coastal Infrastructure

1. INTRODUCTION

Many coastal or near-water engineering projects have large geotechnical components (such as breakwaters and port facilities) that require careful foundation design. In many areas, these near-water structures face the risk of Tsunami-type events, either through tectonic activity (such as Japan or the west-coast of the Americas), submarine slope failure (such as the east coast of the USA or the west coast of the UK (Driscoll et al., 2000)) or large landslides (such as the Lakes of Switzerland (Schnellmann et al., 2006) and other Alpine-lake regions).
In order to design structures to resist such actions, good knowledge of both the phenomenon and its interaction with any structures must be obtained. Tsunami waves, although by no means simple events, have been well studied, and there is a good deal of knowledge pertaining to their characteristics and properties, such as height, run-up and general morphology (Synolakis et al., 2008; Tadepalli and Synolakis, 1996). The same cannot be said for their interaction with structures, particularly where geotechnics are concerned. The possible impacts on soil stress state, washout and scour are not as well studied or understood. A particular concern is the "unseen" impact that very large hydraulic events may have on foundations, even when no external damage to the superstructure is present. Importantly, a number of the possible impacts on geotechnical structures require radically different approaches to mitigate; increasing soil permeability may help to counter the build up of pore

[1] Doctoral Candidate, ETH Zürich, Institut für Geotechnic, Zürich, Switzerland, liam.jones@igt.baug.ethz.ch
[2] Professor, ETH Zürich, Chair of Geotechnics, Zürich, Switzerland, ixa@igt.baug.ethz.ch

pressures, but it would severely increase the potential for scour and wash-out. Thus, it is essential that we have good knowledge of the precise mechanisms at play during Tsunami, before design takes place.

The project discussed here aims to adapt existing, well established, geotechnical modelling techniques (i.e. centrifuge modelling) to the problem at hand. Part of that process is detailed here, with the design of a test-bench, used to thoroughly examine and characterize modelling techniques for later adaptation to a geotechnical centrifuge. The design of this lab-scale test apparatus will be discussed here, along with the challenges and solutions to designing such a device, which themselves illustrate some of the interesting aspects of both Tsunami-type events and geotechnical physical modelling in general.

2. TSUNAMIS AS A GEOTECHNICAL PHENOMENON

Many, if not all, coastal or near-water infrastructure has a large geotechnical component (Tsinker, 2014). Whether it is the construction of breakwaters, harbor facilities, or seawalls and revetments, geotechnical engineering plays a crucial role in design. Additionally, specifically for Tsunami events, many failures of these of these structures are geotechnical. During, or after Tsunamis, breakwaters or sea walls can be seen to have been displaced, rotated or to have been transported away from their original location (Arikawa et al., 2012; Chock et al., 2013b). Generally, the concrete parts of these structures remain intact. The rest of the structure (the geotechnical part), such as the embankment or revetment on which the concrete part sits is either severely damaged or destroyed. Measuring the specific damage to such a structure, particularly internally, can be extremely difficult. In particular, the time-line of such failures may be very important for design, and is almost impossible to ascertain with measurements taken after the event. Methods are available for estimating the "pseudo-static" loads imparted on structures by Tsunami (Nistor et al., 2009) however they do not account for any interaction with foundation systems, and produce quite different design values between different codes (Thusyanthan and Gopal Madabhushi, 2008).

Thus, effects of Tsunamis on the performance of such embankments and gravity structures is not well understood, and assessing their suitability for re-use poses significant problems for those tasked with re-building after a Tsunami. Generally, the approach has been to massively reinforce and enlarge such partially destroyed structures (as in Japan after the Tsunami of 2011) (Raby et al., 2015). The effectiveness of such a strategy is as-yet unknown, and it seems wise not to wait for the next catastrophe in order to find out.

Thus, there remain many questions both about how near-water structures fail and how to design them against such failures. Although many failures are attributed to scour or piping beneath the foundation (Chock et al., 2013a), it is extremely difficult to confirm this from field observations, where the failed super-structure is often transported away from its original foundation. This makes it difficult to assess whether the observed scouring is a cause or a result of the failure of the structure. In order to resolve this, the failure would need to be observed and documented as it happened, something which is only possible though reduced-scale physical modelling in the lab.

3. GENERAL TSUNAMI CHARACTERISTICS AND SIMULATION TECHNIQUES

The "traditional" Tsunami is generated by the large, rapid movement of sub-sea tectonic plates either during or after an earthquake. Although the tectonic displacement may only be of the order of centimeters, it can take place over an area of ocean floor many thousands of square kilometers in area. This small change in the effective depth of the ocean over a discreet area causes the total ocean surface to re-equilibrate, generating a "wave", or waves that can be many tens to hundreds of kilometers in length, which can propagate over an entire ocean (Bryant, 2014). When these large wavelength waves approach the shore, the depth of water in which they propagate decreases. This causes the wave to slow down, and thus increase in height through the shallow water wave equation, which is generally accepted as adequate for deriving the celerity of Tsunami waves (Allsop et al., 2014; Rossetto et al., 2011):

$$c=\sqrt{gd} \quad (1)$$

Where *c* is the celerity, *g* and *d* are gravitational acceleration and water depth respectively.
The term “Tsunami” is also used to describe a number of other events with similar consequences but radically different origins, such as landslide “Tsunamis” or yet more distant, seiche events, more common in Europe (Genevois and Ghirotti, 2005; Rabinovich, 2010; Schnellmann et al., 2006). Given that the aim here is to model the ultimate consequence of such events and not their origins, it is safe here to group these distinct mechanisms under the umbrella term “Tsunami”. Although, qualitatively we can say that the resulting inundating waves are similar (large height, large volume) the specific wave types, forms and behavior can be substantially different. This is one of myriad of reasons why modelling a Tsunami with any accuracy can be extremely difficult.
Allowing for the previous, we can say that Tsunami are generally characterized as a solitary or N-Wave. One fairly simple form of N-wave is described using a hyperbolic secant function (Whitham, 2011):

$$n(t)=\varepsilon H\left(ct-X_2\right)\text{sech}^2[\gamma\left(ct-X_1\right)] \quad (2)$$

Where *n* is the water surface profile, *H* the desired wave height, ε and γ are dimensionless scale factors relating to amplitude and steepness respectively. X_1 and X_2 are geometric scale parameters, and control the shape of the wave, allowing for symmetric or non-symmetric positive and negative pulses (Figure 1).

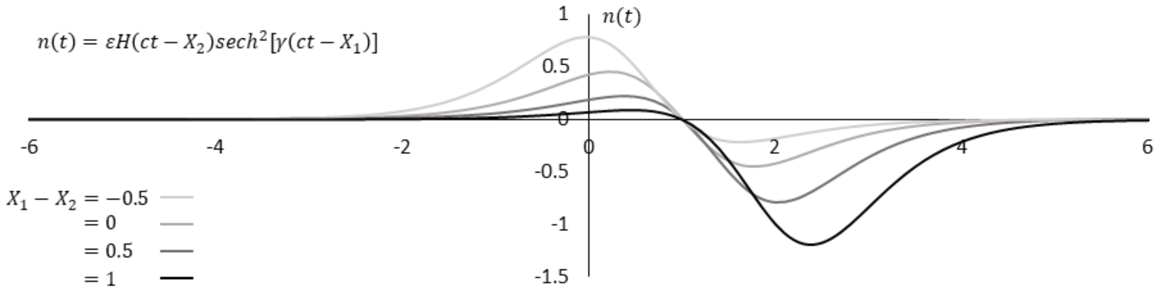

Figure 1. Generalised “N-Wave” after Whitham (2011) showing the effects of the shape parameters X_1 and X_2

The purpose of illustrating this point, is that it has specific implications for the design of any “simulation” machine. Both these colossal wavelengths and large negative amplitudes are far out of the reach of a traditional paddle-type wave generator using in most geotechnical modelling set-ups.
One successful technique used to model Tsunami-type waves employs what is known as a “Tidal Generator”. A Tidal Generator is essentially a submerged water reservoir (charge tank) that discharges into an open body of water under a pressure differential (Figure 2). By changing the air pressure within the closed reservoir, the water level of the open body can be raised or lowered very precisely. This can be done in cycles, to simulate the ebbing and flowing of tides (hence the name) (M.J.Wilkie 1952). However, rapid changes in pressure in the reservoir can produce the shock-type waves characteristic of a Tsunami. The pressure inside the chamber is controlled via the application of vacuum or compressed air to the charge tank, so air must applied or evacuated rapidly. Because the flow of water is controlled by air pressure, a comparatively small amount of mechanical effort is needed to manipulate large volumes of water.
Such a set-up has been effectively employed in previous research, at reduced scale, focusing on the specific reproduction of the Tsunami wave-form, both near and on-shore (Rossetto et al., 2011).
The key advantage of such a device is the theoretically limitless wavelength able to be produced. Such a system can also easily reproduce the initial negative amplitude phase of a Tsunami. However, practically, there are limits on the devices capabilities due to the volume of water that can be stored in the tank. In order to model realistic scale Tsunami, the tank must be very large. Although this is of little concern for traditional lab scale experiments, it makes adaptation to a geotechnical centrifuge

challenging. Restrictions on model size in a centrifuge are based both on space and weight, thus even if a large volume of water could be stored on the machine platform, its weight (when accelerated up to 50g, 100g or higher) would make the set-up impossible.

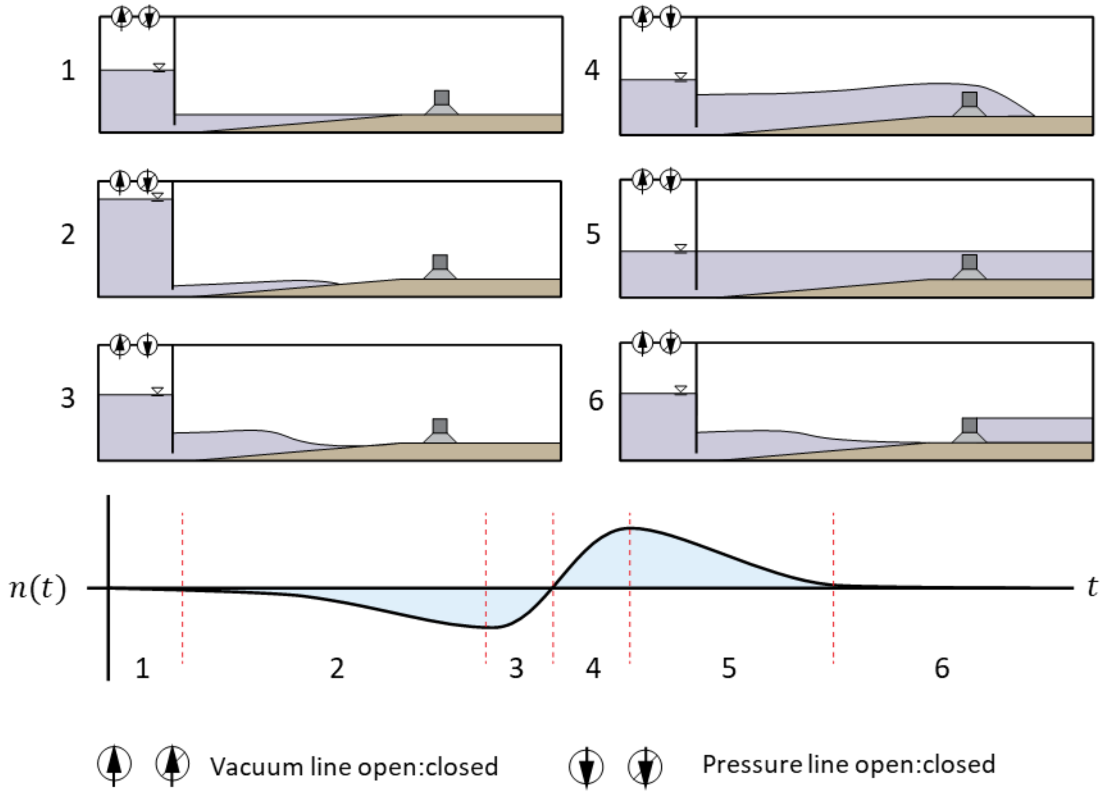

Figure 2. Schematic diagram and mechanical function of a "Tidal Generator" (Upper) and general "Tsunami-Type" surface elevation (lower) profile. 1) Initial State 2) Drawdown 3) Positive pulse 4) Model Inundation 5) Steady water surface 6) Return to initial state

Another (significant) limit on the outlined concept is the inability to model a Tsunami wave of constant height. In order for the machine to work, and generate flow, there must be a hydraulic gradient between the outflow of the tank and the end of the model space. This means, either the height of the wave must be constantly increasing, or there must be some other boundary condition, such as a drain, on the far side of the model.

4. PROPOSED DESIGN

For the purposes of calibration and testing, a lab scale experiment is designed and constructed. This prototype is designed to operate without the additional gravitational acceleration provided by a geotechnical centrifuge, with the purpose of testing the Tsunami generation system. It will also be used to investigate, and test, various data acquisition and model construction techniques which will be used later for centrifuge models. The model is designed to have as much similitude with the final centrifuge apparatus as possible, including dimensions, equipment and mechanical design. One concession is made with regard to geometry, where the prototype is roughly half the length of the centrifuge model, owing to limit on available lab space and practical constructability. The apparatus is designed to replicate scales of 1:50 ~ 1:100 hence, wavelengths of 5-10m, and heights 0.01-0.1 m. The model area is 1.6m in length, and can accommodate models 0.3m in out-of-plane breadth (Figure 3). Models consist of a long inclined shoaling area made up of sand or other test material. At the end of the model is situated the prototype structure. Ideally, the model space would extend a considerable distance behind the model, to accommodate the run-up of the Tsunami wave, however that was not practical here due to space restrictions.

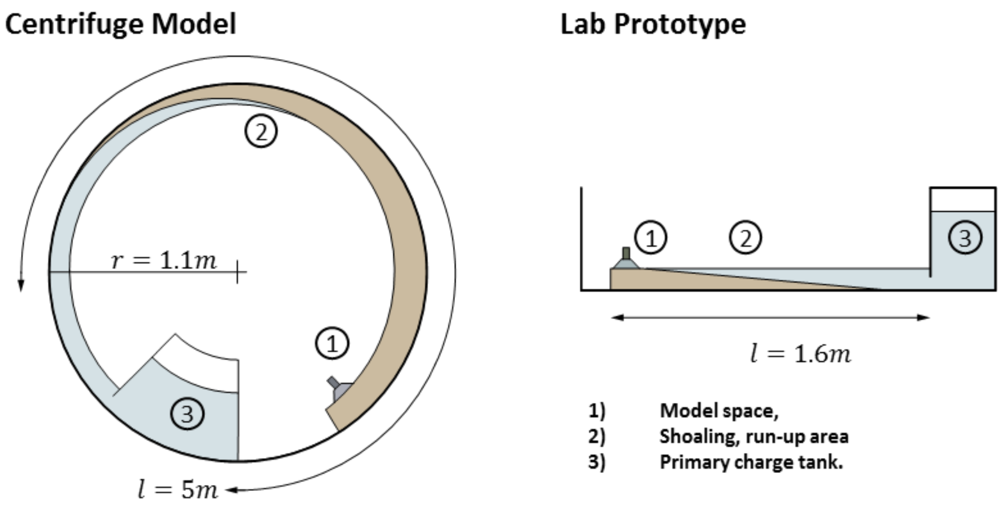

Figure 3. Proposed centrifuge experiment (left) and new lab-scale testing apparatus (right) with approximate dimensions

To overcome the previous limitations with the "tidal generator", a modified generator design is proposed which allows for re-circulation of water after passing over the model area. Such a design has the advantage of both minimizing the size of tank required in the apparatus and effectively allowing an infinite wavelength event to be modelled.

Such a system could be constructed using a traditional pump, which cycles water from the end of the model area and back into the tank. However, this method has a number of disadvantages: Firstly the pump would have to have an extremely high performance, able to achieve flow rates in excess of $1m^3$ per minute for the model discussed here. Secondly, the pump would also have to be designed to resist the very high operational acceleration of a geotechnical centrifuge, which would come at extremely high mechanical and monetary cost.

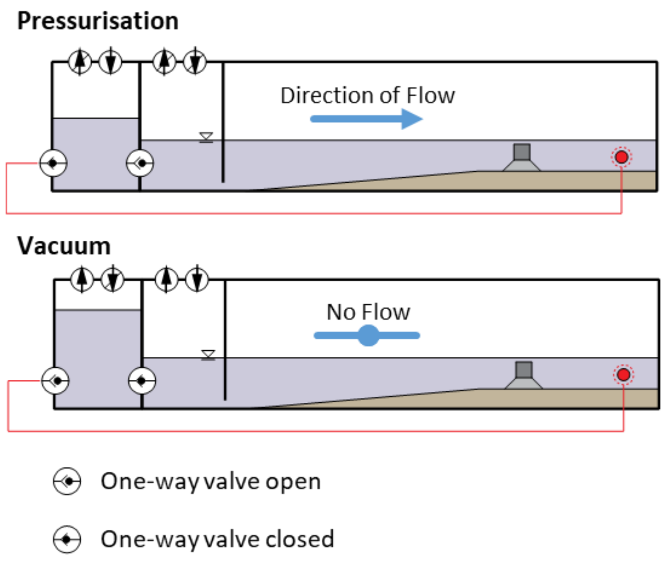

Figure 4. Modified Tidal Generator design including a new recirculation system. The two phases are shown Pressurisation (Top) atmospheric pressure is allowed into the tank. This pressure forces closed the left hand one-way valve, and forces open the right. Water flows though the right hand side and into the model area. Vacuum (Bottom) pressure in the tank is dropped, pulling open the left hand one-way valve and shutting the right. Water is drawn from the end of the model area and into the secondary tank

As such, the desired recirculation is achieved simply by adding an additional charge tank that both pulls water from the end of the model area and then injects it into the original "primary" tank (Figure

4). It works in exactly the same fashion as the primary tank, however, the addition of two one-way valves means the water can only flow in and out of the tank in one direction. Upon application of vacuum to the tank, water is drawn in from the far side of the model area, upon pressurization; water is discharged into the main charge tank. The system works essentially like bellows, used for providing air to a furnace or fire. Adding an additional parallel re-circulation tank, operated out of phase from the other allows for a continuous flow of water around the model. The systems functions to provide a fairly steady amount of continuous volume flux which can be attenuated using the main charge tank as a sink if desired.
Pressure within each tank is regulated via a digital proportional valve. A target pressure is transmitted to the valve, and it opens or closes ports to vacuum or atmosphere until the target is reached. The valves are controlled via computer, in an open loop system, where commands are sent from the PC to the valve, and the valve passively reports internal pressure readings (Figure 5).
A vacuum pump is also specified for use with the apparatus. This is done simply though obtaining the first derivative of the desired wave profile with respect to time, to obtain the volume flux. Using the geometry of the tank, it is then possible to calculate the required pressure gradient with respect to time within the tank. This can then be used to specify the required pump. This results in a fairly large pump requirement due to the large increase in celerity at higher levels of acceleration.

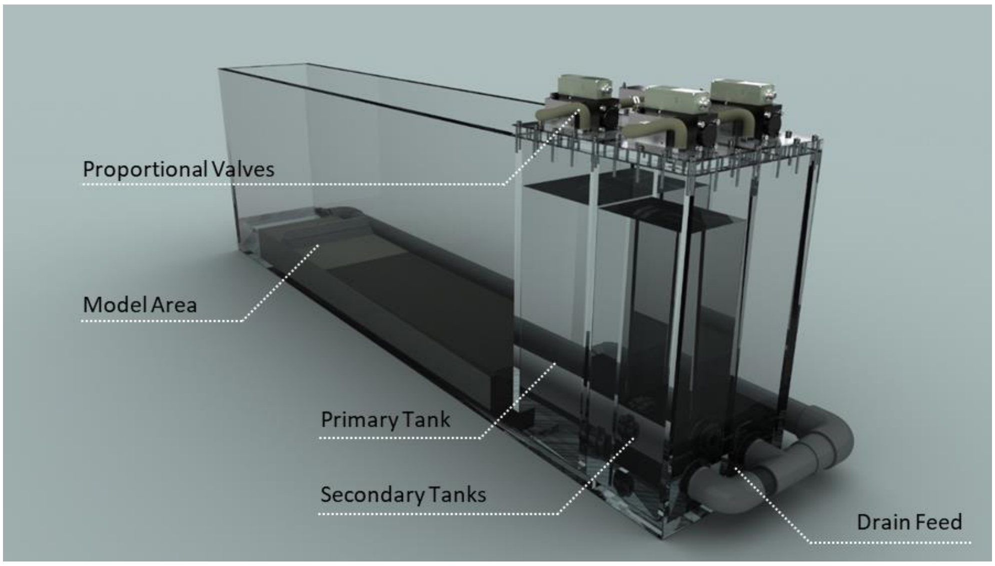

Figure 5. Illustration of the constructed lab-scale testing apparatus, showing the model area, control valves and secondary tanks

It should be noted here, that the purpose of this device is not to model the generation or propagation of Tsunami with a great deal of accuracy. The set-up is designed to capture the broad characteristics of such events, and cover a sufficient envelope such that the most extreme aspects of such events can be simulated. The purpose here is to model and test the interaction between such events and geotechnical structures in as general and widely applicable sense as possible, covering a wide gamut of scenarios rather than aiming to reconstruct specific events.

5. CONCLUSION AND OUTLOOK

A new procedure for simulating the interaction between Tsunami-type events and their interactions with geotechnical structures has been described and detailed. The apparatus is currently under construction, with the aim of testing and refining techniques for later use in the scaled gravity environment of a geotechnical centrifuge.
The apparatus is still in the beginning phases of testing and commissioning, but initial qualitative findings give a hopeful outlook for future experiments aimed at understanding this complex and little

understood phenomenon. Future publications will detail the calibration and ultimate performance of the set-up.

The interaction between geotechnical structures and hydrodynamic or Tsunami-like events is an interesting and challenging field, where much remains to be discovered. However, recent interest has lead to some interesting discoveries and raised some new questions relating to precisely how such structures fail, and how to design against these failures (Miyamoto et al.; Tsurugasaki et al.). These discoveries come at a time where impacts from such events are becoming far more destructive, thanks to increasing urbanization (especially in coastal areas) and the ever increasing frequency of catastrophic metrological events due to climate change. This makes the study and application of potential resilience measures extremely important. Part of this effort is the resilience of coastal or near-water infrastructure to such events, whose constructions are largely geotechnical in nature. The hope of this project is to open-up a new avenue for future research and design schemes aimed at exploring this difficult and ever evolving area of design.

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