ON THE GENERATION OF TSUNAMI IN A LARGE SCALE WAVE FLUME

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This paper presents very long, i.e. real tsunami-like wave generation in a large scale wave flume using a piston type wave maker. Waves of periods between 30 s and more than 100 s were generated at 1 m water depth using two different approaches: (i) deriving the wave board motion directly by integration of the water surface elevation, composed of a different number of solitons (sech^2 waves) and (ii) using an iterative self correcting method (SCM). The importance of very long wave generation instead of solitary waves and the necessity for long testing facilities is discussed and results from GWK experiments are presented for single pulses (elongated solitons), N-waves and real tsunami records, either approximated as a combination of solitons or applying the SCM to the time series directly.

Keywords: Long waves; Tsunami; Solitons; N-Waves; Wave Generation; Self Correcting Method (SCM)

INTRODUCTION

Ever since the occurrence of the 2004 Indian Ocean Tsunami, these extreme long wave events in near shore areas and their effects on beaches and on coastal structures have been investigated by many researchers. The effect of tsunamis on the coastline depends on the bathymetry and it varies from place to place. Thus, it is important to understand tsunami wave propagation, shoaling, reflection, transmission, breaking, run-up and overtopping and basically there are two ways to investigate these effects, numerical simulations and/or laboratory experiments. For the former there have been lots of development in the last years covering all scales of a tsunami from the source point (generation) over propagation on the ocean and at the coast to the modeling of nearshore processes. Despite this appreciable progress in numerical modeling, there is still a need for laboratory experiments, for which the major challenge is the proper scaling of nonlinearity (H/d) and dispersion ($(d/L)^2$) of a real tsunami. Almost all experimental tsunami studies in the past were based on solitary waves, probably because these waves have a strong analytical background and further they allow the use of existing wave flumes as they can relatively easily be generated by a piston type wave maker. However, Madsen et al. (2008) could clearly demonstrate that in particular in the shallow waters near the coast this paradigm is actually not associated with a real tsunami, which is known to be much longer and less steep than a solitary wave where nonlinearity and dispersion are in balance by definition.

In order to generate longer waves and to simulate real tsunamis (e.g. based on measurements) in the laboratory recently some other promising forms of generation have been proposed using a pneumatic wave maker (Rossetto et al., 2011) or a pump-driven wave maker (Goseberg et al., 2013). Nevertheless, these techniques have to face other difficulties like turbulence/breaking/compressed air-water phases near to the generation point or being only applied so far on a rather small scale, i.e. a tank length of about 30 m. Hence, generating stable long waves without any reflection is still questionable and many improvements need to be carried out. The major challenges are to generate a stable long wave from the very beginning, i.e. at the generation region the wave should be stable in order to be reproduced numerically without any limitations, and to carry out the tests in a long wave flume to properly scale the length and height of a real tsunami.

The Large Wave Flume (Großer Wellenkanal, GWK) at Forschungszentrum Küste (FZK) in Hannover, Germany has a piston type wave maker with 4 m stroke and a total length of about 300 m and could be an excellent candidate to meet these challenges. However, the flume was actually built and has always been used for large scale experiments on wind (comparably short period) wave interaction with sediments, plants or coastal and offshore structures, which are usually carried out at water depths between 3 – 5 m. No one has ever tried to generate very long waves with periods of O(100 s) at water depths of O(1 m) in GWK or any other similar wave flume. Probably this led Rossetto et al. (2011) to conclude that none of the existing large scale testing facilities, equipped with a piston type wave maker will be able “to produce long period or trough-led waves”, which gave us enough motivation to try it out and possibly be the first to use GWK as a tsunami testing facility.

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EXPERIMENTAL SET-UP

With about 300 m length, 5 m width and 7 m depth GWK is one of the largest facilities of this kind worldwide and usually used for large scale studies in coastal or maritime engineering. Waves are generated with a piston type wave maker with a maximum stroke of 4 m. The oil hydraulic driving system can move the wave board with a maximum velocity of 1.7 m/s and a maximum acceleration of 2.1 m/s^2, such that wave heights of up to 2 m can be generated at typical periods between 3 s and 8 s and water depths between 4 m and 5 m. At the end of the flume was a 1:6 sloped asphalt dike with the dike toe at x = 251.5 m. For the present study the water depth was reduced to 1 m and some of the wire wave gauges installed along the flume were lowered to the bottom in order to record the water surface elevation at x = 3.6 m, 50 m, 51.9 m, 55.2 m, 60 m, 225 m, 230 m, 235 m and 245.33 m off the wave maker. Figure 1shows a sketch of the experimental set-up. The scaled side view of the whole flume in Figure 1 a has been shown in order to provide an impression of the scale of the experiments, while the maximum stroke of the wave board and the individual gauge positions can be estimated from the scaled detailed view in Figure 1 b.

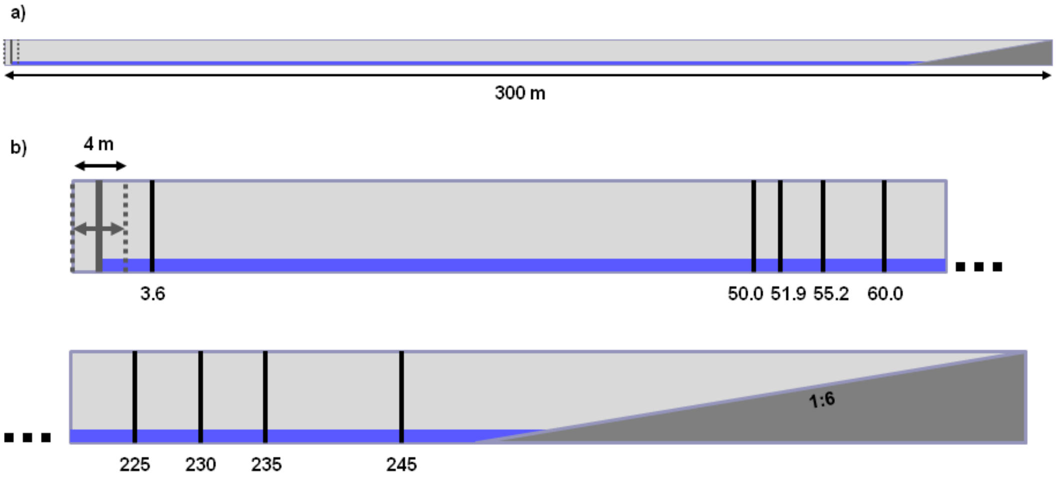

Figure 1: Experimental set-up for tsunami generation tests in GWK. a) Scaled side view of the whole flume; b) scaled detailed view of the beginning and end of the flume with wave gauge positions.

As the gauges are usually not used in such small water depths they were thoroughly calibrated prior to the experiments and additionally a very well validated numerical model (e.g. Sriram et al., 2006; Sriram et al., 2007) based on fully non-linear potential flow theory (FNPT) has been applied to verify the measurements and vice versa. As the wave heights are critically small it is further essential for an accurate generation of these long period waves with a piston type wave maker that there is no water leakage at the edges of the wave board (e.g. Grilli et al., 2004, Sriram and Ma, 2012), but as the backside of the wave board is dry at GWK this prerequisite is met anyway.

METHODOLOGY OF GENERATION

The generation of tsunamis in a laboratory flume starts with the essential question which waves actually are most representative for a real tsunami. As stated before solitary waves have often been used in previous studies, but due to their inherent assumption of balance between nonlinearity and dispersion pure solitary waves become very short in shallow waters. However, in general the soliton approach seems to be reasonable and Chan and Liu (2012) showed that tsunami measurements can be well represented by a combination of sech^2 waves, independent on water depth:

$$\eta(t) = \sum_{i=1}^{N} H_i \,\mathrm{sech}^2 \omega_i (t - (t_0 + t_i)) \tag{1}$$

where H_i and ω_i are the height and frequency of wave component i and t_0 and t_i are time shifts of the whole wave and each component, respectively. This generic approach covers the classical solitary wave if the frequency is chosen according to solitary wave theory (e.g. Dean & Dalrymple, 1991), but also describes elongated solitons (e.g. Didenkulova et al., 2009), N-waves (e.g. Tadepalli & Synolakis, 1994) or allows for a fit to field measurements as in Chan and Liu (2012). The latter was applied to measurements of the 2011 Tohoku tsunami in Chan and Liu (2012), here we use the measurement of the

2004 Indian Ocean tsunami by the yacht "Mercator", anchored in 14 m water depth about 1.6 km in front of the coast of Phuket, Thailand, as an example for the representation of a real tsunami by different sech^2 waves. Figure 2 shows the measurements together with a pure solitary wave at the corresponding water depth, an elongated soliton fitted to the tsunami crest and a fit of the whole time series by three sech^2 waves with H_i = [-3.1 3.8 -1] m; ω_i = [0.0042 0.005 0.01] s^{-1} and t_i = [600 1000 1399] s, respectively. It is seen that due to the shallow water depth the solitary wave does not represent the real tsunami at all and although the elongated soliton resembles the shape of the wave crest reasonably it does not cover the leading trough, which might be important at least for the wave run-up. An N-wave, composed of a positive and negative elongated soliton might have worked better, but is not explicitly shown as we found that the best representation can be achieved by a combination of three sech^2 components, which we therefore used on an approximate scale of 1:100 for the present study.

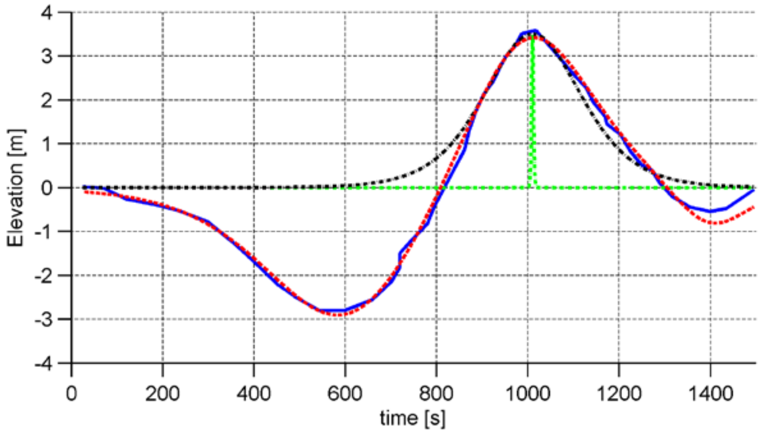

Figure 2: Representation of 2004 Indian Ocean tsunami recorded by yacht "Mercator" at a water depth of 14 m (Rabinovich & Thomson, 2007). Field measurement (blue solid) and fitted sech^2 waves (red dashed); additionally a pure solitary wave and an elongated soliton are shown by the dash dotted green and black line, respectively.

In order to generate the desired profiles we used the approach of Synolakis (1990), in which for shallow water waves in a particular water depth d the wave board motion $\xi(t)$ can be directly obtained from the water surface elevation $\eta(t)$ by integrating

$$\frac{d\xi}{dt}=\frac{c\eta}{d+\eta}=\frac{\sqrt{g(d+H)}\eta}{d+\eta} \tag{2}$$

in which H is the wave height of the whole wave. Synolakis (1990) used a 4th order Runge-Kutta scheme for the numerical integration of (2), but for very long small amplitude waves like in the present study also lower order integration methods are sufficient to obtain the stroke signal.

The above approach has been used in almost all cases of the present tests, but additionally we tried the application of a self-correcting method (SCM) for tsunami wave generation. The SCM was initially proposed by Daemrich et al., (1980, 1988) for regular and random wave generation, later used by Chaplin (1996) and Schmittner et al., (2009) for focused wave generation and recently extended for focused wave generation over variable water depth by the authors (Fernandez et al., 2014). The objective of this method is to generate a particular target wave profile at a certain position in a flume by an iterative (self-correcting) process. The SCM converges very quickly, usually after only 2 - 4 iteration steps, which can either be done in the wave flume directly or if available using a numerical wave tank in advance and applying the obtained control signal to the wave board of the physical flume. This latter approach has been applied for the present study using the above mentioned FNPT model. The principal algorithm of the SCM is sketched and shortly explained in Figure 3. More details and applications of the SCM including the numerical model can be found in Fernandez et al. (2014).

The SCM is applicable with a minimum knowledge of the wave generation system (electronics and mechanical parts) and theoretically it can be used with flap or piston type wave makers or even with pneumatic (Rossetto et al., 2011) or pump generators (Goseberg et al., 2013). The only requirement is that the target wave can be physically meaningful described in frequency domain by linear sine waves, which might not necessarily be the case for highly nonlinear waves or solitons. However, a detailed argument about this fundamental issue is beyond the scope of the present study and we will only shortly discuss the general applicability of the SCM to generate a scaled down measured tsunami wave.

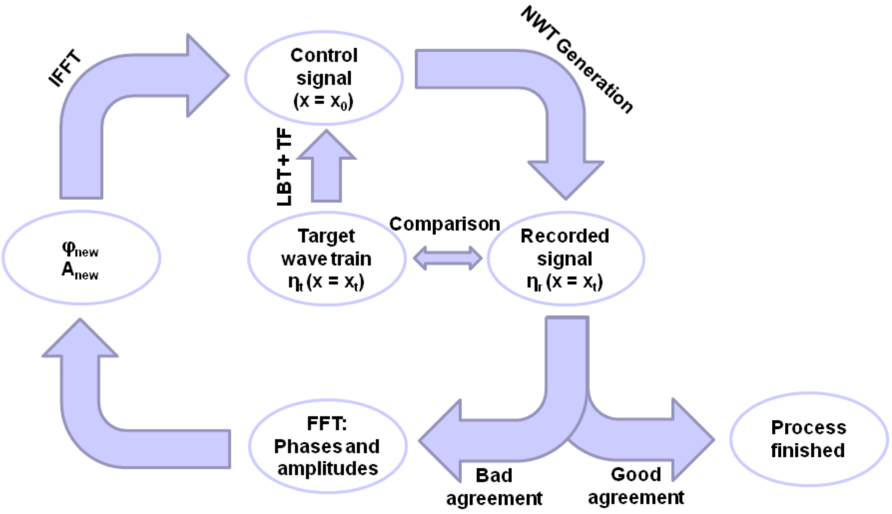

Figure 3: Principal algorithm of the SCM. The target wave train is shifted to the wave board using a linear back transformation (LBT) in frequency domain and the wave board motion is obtained using a transfer function (TF); the generated wave is recorded at the target position and compared with the target wave; if the agreement is bad a new wave board motion is obtained by adjusting the phases and amplitudes of the former control signal spectrum and the iteration is continued until good agreement with the target signal is obtained and the process is finished.

RESULTS AND DISCUSSION

In order to show the feasibility of long wave generation with a piston type wave maker in GWK we exemplarily present three different waves using the generic approach of soliton superposition, equation (1) and (2), and applying the SCM to a scaled down measurement of a real tsunami. The test cases cover two artificial waves in terms of an elongated soliton (1 sech^2 profile) and an N-wave (2 sech^2 profile) as well as two real tsunami waves, approximated by a 3 sech^2 profile and by applying the SCM. All tests were carried out at a water depth of 1 m and Table 1 summarizes the wave heights, periods and time shifts of the individual wave components using the generic approach and the total wave height and period estimated from the target time series for the SCM, respectively.

Table 1: Overview of wave parameters for the presented test cases

Type	H1 (m)	H2 (m)	H3 (m)	T1 (s)	T2 (s)	T3 (s)	t1 (s)	t2 (s)	t3 (s)
1 sech^2 profile (Elongated soliton)	0.06	-	-	30	-	-	-	-	-
2 sech^2 profile (N-wave)	-0.02	0.07		20	20	-	20	30	-
3 sech^2 profile (“Mercator tsunami”)	-0.03	0.04	0.01	126	126	63	60	101	140
SCM (“Pago Pago” tsunami)	0.10	-	-	110	-	-	-	-	-

In the following we will present and shortly discuss the results for each of the individual experiments in GWK. Additionally the numerical wave tank (NWT) based on FNPT has been applied for all test cases and the results are presented as well for comparison. In this sense we can serve two purposes if the results are in agreement: (i) the measurements of the GWK wave gauges, which were actually not intended for such “small” water depths of 1 m, can be verified and (ii) the numerical model would be validated for long wave generation. The latter is of particular interest considering another paper of the proceedings (Sriram et al., 2014), where the FNPT model has been used for the simulation of tsunami propagation and run-up in near shore areas.

Elongated soliton (1 sech^2 profile)

We first consider a single pulse in terms of an elongated soliton with a wave height and period of $H = 6$ cm and $T = 30$ s, respectively. Assuming a scale of 1:100 this corresponds to a 6 m wave with 300 s period at 100 m water depth and might be considered as typical for a landslide tsunami, which is usually shorter than an earthquake tsunami (cf. Figure 2). For comparison, a pure solitary wave of the same height had a period of about 90 s at 100 m water depth, i.e. about 9 s at 1 m depth on a 1:100 scale.

The results for this test case are presented in Figure 4, which shows the wave board motion and the water surface elevation at three different locations along the flume, at x = 0 m (at the wave board), x = 50 m and x = 225 m. The GWK measurements are represented by the solid blue lines and additionally the results of the numerical simulations are plotted as dashed red lines.

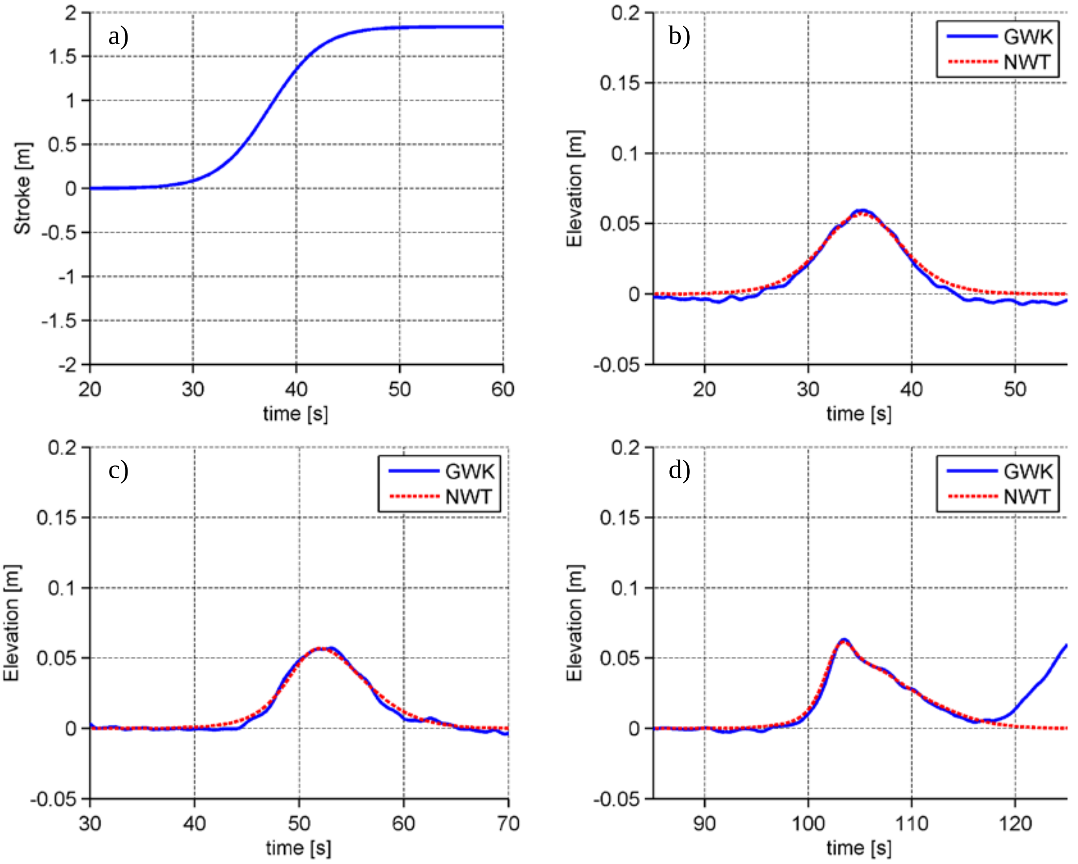

Figure 4: Elongated soliton (1 sech^2 profile) with H = 0.06 m and T = 30 s. Stroke (a) and water surface elevation at the wave board x = 0 m (b), x = 50 m (c) and x = 225 m (d). The solid blue line corresponds to the measurements at GWK and the dashed red line shows the results of the FNPT model.

The very good agreement between the measurements and the numerical results approve both, the proper calibration and operation of the wave gauges and the validity of the NWT to simulate such long waves accurately. The obvious deviation at x = 225 m (Figure 4 d) does not alter this conclusion as it is just due to the reflection from the 1:6 slope in GWK, which was not included in the NWT where for numerical reasons a sponge layer was implemented instead. The comparably short period of the wave (wave length: $L \approx 94$ m) has been chosen by intention as it allows for observing the transformation of the wave along the flume. While at x = 0 (Figure 4 b) the wave is completely symmetric a slight asymmetry and steepening of the wave front can be deduced already at x = 50 m (Figure 4 c), which is clearly pronounced about two wave lengths further at x = 225 m, where also the start of the separation of a first solitary wave at the front (e.g. Madsen et al., 2008) can already be guessed.

From the time series of the wave board motion it can be seen that with a maximum stroke of about 1.8 m this wave is well within the limits of the GWK wave maker capabilities (4 m maximum stroke). In fact, for single pulses the stroke almost linearly depends on the wave height, i.e. for a 30 s soliton at 1 m water depth the maximum achievable wave height in GWK is about 13 cm.

N-wave (2 sech^2 profile)

It was demonstrated by (Tadepalli & Synolakis, 1994) that a wave of varying polarity with a leading trough (N-wave) leads to a larger wave amplification and run-up on a beach than a wave of just positive polarity. Later this effect has been attributed to the wave front steepness by Didenkulova et al. (2007). Furthermore, N-waves became popular in tsunami wave studies as a real tsunami is often observed to have a leading trough, i.e. when it approaches the coast the water recedes from the coastline first before the inundation due to the following wave crest. Here we consider an N-wave as a combination of two elongated solitons (2 sech^2 profile) with a period of 20 s each and a time shift between the wave trough and crest of 10 s, which results in a total period of 30 s, comparable to the single positive soliton discussed above. The wave is asymmetric in terms of trough and crest elevation, which are H_t = 2 cm and H_c = 7 cm, respectively, giving a total wave height 9 cm. Figure 5 shows the wave board motion and the water surface elevation for this wave in analogy to the results for the single soliton presented above.

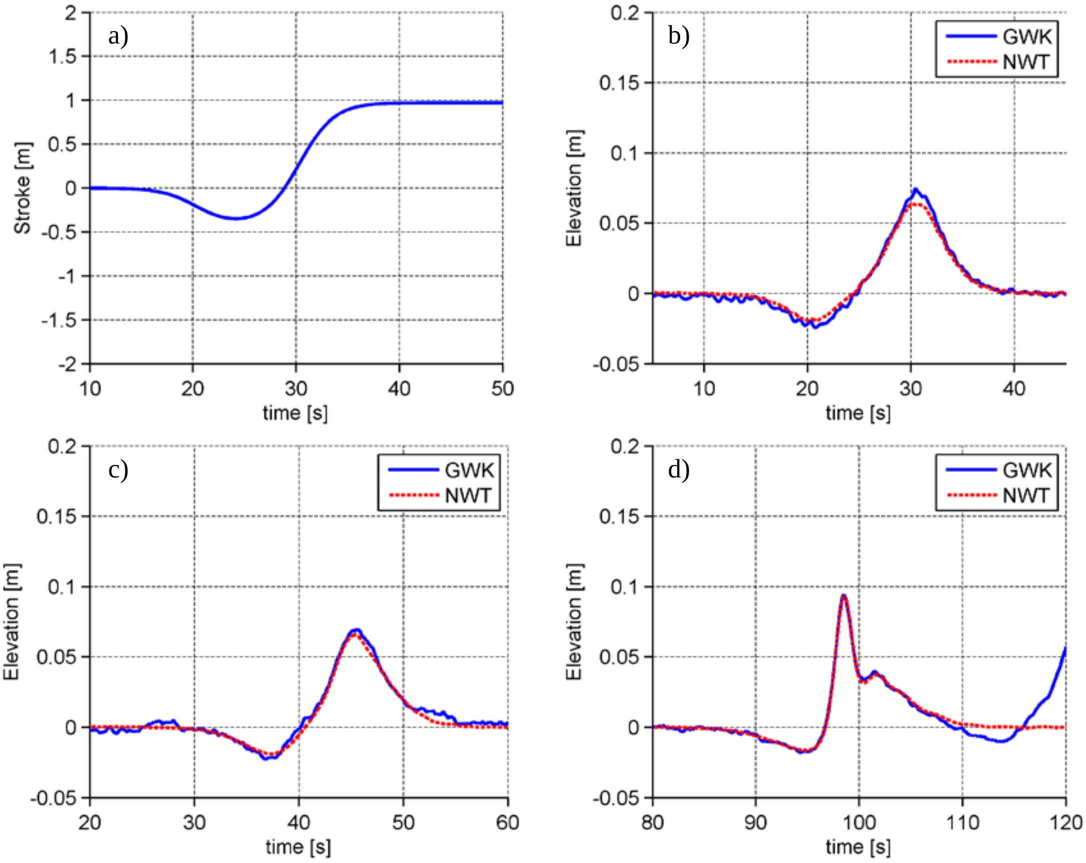

Figure 5: Asymmetric N-wave (2 sech^2 profile) with H = 0.09 m and T = 30 s. Stroke (a) and water surface elevation at the wave board x = 0 m (b), x = 50 m (c) and x = 225 m (d). The solid blue line corresponds to the measurements at GWK and the dashed red line shows the results of the FNPT model.

Neglecting the slight deviations at the wave board (Figure 5 b) and ignoring the reflections from the slope at x = 225 m (Figure 5 d) the agreement between the laboratory measurements and the numerical model results is expectedly very good. Due to the 50 % larger wave height compared to the 1 sech^2 profile above the transformation of the N-wave is stronger and the steepening of the wave front more pronounced. It is interesting to note that despite the larger wave height the total stroke of the wave board is only about 1.3 m (Figure 5 a), which is more than 25 % less than the required stroke for the elongated soliton above. Obviously for a combination of sech^2 waves the relation between stroke and wave height becomes less straightforward and depends on the height and period of the individual components as well as the time shift between them. For the present periods and time shift and a ratio between trough and crest elevation of 2/7 the maximum achievable total wave height with a 4 m stroke is about 28 cm.

“Mercator” tsunami time-series (3 sech^2 profile)

In both cases considered so far the waves had a rather short period of “only” 30 s and we still need to demonstrate that also much longer earthquake tsunamis can be reproduced in a large wave flume by a piston type wave maker. For this purpose the recording of the 2004 Indian Ocean tsunami by an echo sounder on the yacht Mercator, already shown in Figure 2, was approximated by 3 sech^2 waves and scaled down by 1:100. This results in a total wave height of about 6.4 cm and an approximate total period of about 120 s. The water depth was kept at 1 m although it should have been actually reduced to 14 cm, but the deviation was accepted for the present purpose of demonstrating the capabilities of wave generation with a piston type wave maker. Figure 6 shows the corresponding wave board motion and the water surface elevation at the same positions along the flume as before. In addition to the GWK measurements and the NWT results also the scaled down field measurements have been plotted as black dots for reference.

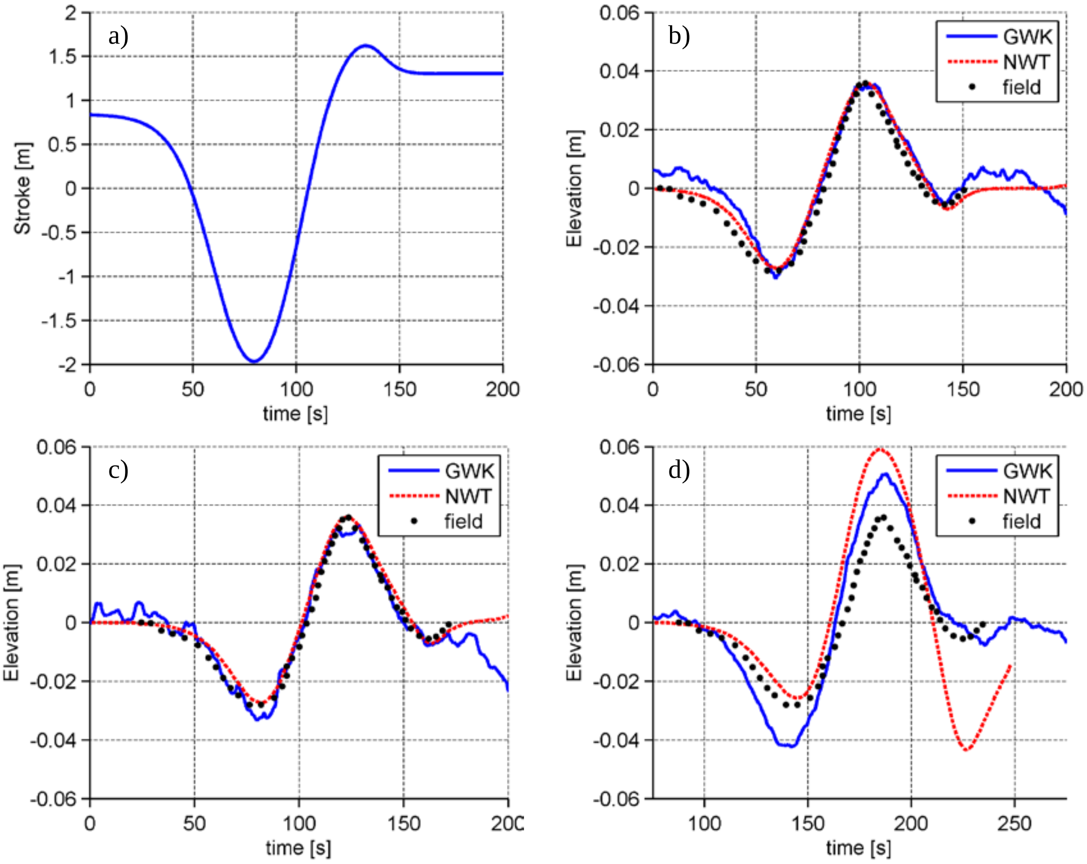

Figure 6: Indian Ocean tsunami 2004 recorded by yacht Mercator on a 1:100 scale (except for water depth) approximated by a 3 sech^2 profile. Stroke (a) and water surface elevation at the wave board x = 0 m (b), x = 50 m (c) and x = 225 m (d). The solid blue line corresponds to the measurements at GWK, the dashed red line shows the results of the FNPT model and the black dots represent the scaled down field measurements.

The wave board motion (Figure 6 a) shows that with a maximum stroke of about 3.6 m the chosen scale of 1:100 for this particular real tsunami time series is rather at the limit of the wave maker in GWK. It should be noted in this context that if the water depth would have been reduced the maximum achievable wave height would be even smaller. The agreement between GWK and NWT data is almost perfect as expected, but also the fit with the field measurements is more than convincing, at least at the wave board (Figure 6 b) and 50 m behind (Figure 6 c). The clear deviations at x = 225 m (Figure 6 d) are due to reflections, which were not present in the field (at least not within the duration of the measurements). In GWK the reflections can be easily explained by the 1:6 slope at the end of the flume and they demonstrate the necessity for conducting tsunami experiments with very long waves flume only in flumes, which are sufficiently long (at least in the order of one wave length). For the NWT reflections were actually not expected and indicate that the sponge layer was not working properly for this very long wave.

"Pago Pago" tsunami time-series (SCM)

Based on the presented results we may already conclude that the generation of tsunamis requires a large scale resp. long flume and it is very well possible to generate tsunami-like waves as a combination of solitons (sech^2 waves) with a piston type wave maker. However, with the chosen methodology so far the desired water surface elevation is generated directly at the wave board and the wave will undergo certain transformation (depending on dispersion and nonlinearity) as it travels along the flume. If one is interested in a particular wave at a certain position in the flume or on a slope this methodology might fail. Therefore we also tried the application of the Self Correcting Method (SCM) to the generation of a measurement of the 2009 Samoa tsunami, recorded by a tide gauge at Pago Pago harbor (Zhou et al., 2012; Didenkulova, 2013). The water surface elevation was scaled down by 1:37, again disregarding the water depth, and the target location was chosen to be at x = 225 m. The iteration has been done with the numerical wave tank and already after 2 correction steps the solution converged. The obtained wave board motion has then been applied in GWK and is shown in Figure 7 together with the results at the target location.

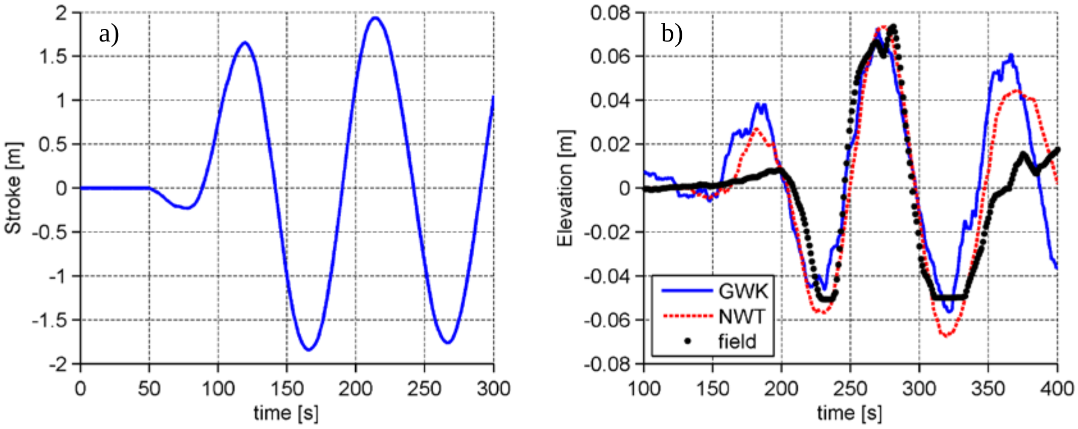

Figure 7: Samoa tsunami 2009 recorded in Pago Pago harbor on a 1:37 scale (except for water depth) generated with the SCM. Stroke (a) and water surface elevation at the target location, x = 225 m (b). The solid blue line corresponds to the measurements at GWK, the dashed red line shows the results of the last iteration step with the FNPT model and the black dots represent the target signal in terms of the scaled down field measurements.

The stroke (Figure 7 a) again is more or less at the limit of the wave maker, which explains the rater odd scale of 1:37, which has been chosen by intention in order to present the maximum achievable scale in GWK for this particular wave. Actually the wave board motion is reminiscent of a periodic wave rather than a transient wave event like a tsunami and in fact this is also reflected in the water surface elevation (Figure 7 b), which for the numerical simulation and the GWK data shows significantly overemphasized wave crests before and after the main wave compared to the field measurements. Furthermore, the agreement between the measurements in GWK and the NWT results is considerably worse compared to the cases before, although the same wave board motion has been used. It could be argued again that this is due to the different boundary conditions at the end of the flume (slope vs. sponge layer), but this has not been investigated further as well as neither have the deviations from the target signal. As the agreement with the main wave is reasonable it can be concluded that the SCM in principle might be applied also for tsunami wave generation in the laboratory, but there are obviously still some open issues left for optimization.

CONCLUSIONS

The main objective of this paper was to show the feasibility of very long, i.e. real tsunami-like wave generation with a piston type wave maker in the laboratory. The need for considering very long waves instead of pure solitary waves for tsunami experiments was pointed out by Madsen et al. (2008) and we shortly presented recently suggested new techniques for their generation ((Rossetto et al., 2011; Goseberg et al., 2013) and discussed the advantages and disadvantages of these novel techniques. In particular the difficulties at the generation point, like high turbulence levels or air water mixtures, could be avoided by using a traditional type of wave maker. Therefore we used a generic combination of solitons (sech^2 waves), as proposed by Chan and Liu (2012), to describe tsunami-like waves from elongated solitons (1 sech^2 profile) over N-waves (2 sech^2 profile) to real tsunami records approximated by a 3 sech^2 profile, and generated these waves in GWK. The wave board motion was derived by simple integration of the water surface elevation and by the presentation and discussion of exemplary results we could approve the chosen methodology as well as even more the general feasibility of generating waves with periods of more than 100 s with a piston type wave maker.

In addition we tested the applicability of a self correcting method (SCM) to tsunami wave generation in order to produce a target water surface elevation at a particular location in the flume, considering all transformations the wave might undergo as it travels along the flume. By the example of a tsunami field measurement the methodology and the capabilities of this approach were demonstrated. The reasonable results within the major part of this example wave allow to assess the SCM in principal to be applicable for tsunami wave generation, even if some considerable deviations at the beginning and end of the target time series suggest for more research on that topic.

We may conclude that the primary objective of this paper has been met, by demonstrating through different examples that unlike the assumption of Rossetto et al. (2011) it is very well possible to generate very “long period or trough led waves” with a piston type wave maker and to use large scale wave flumes like GWK for tsunami experiments. Despite the very good results of the presented test cases it should be kept in mind that the wave heights were admittedly rather small and the scale of the experiments was majorly limited by the available stroke of the wave maker. However, this issue shall be addressed in another paper under preparation (Schimmels et al., 2015), in which we also present more results of the tsunami generation tests in GWK.

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