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Tsunami generation in a large scale experimental facility

Stefan Schimmels [a,*], V. Sriram [b], Ira Didenkulova [c,d]

[a] Forschungszentrum Küste (FZK), Merkurstraße 11, 30419 Hannover, Germany
[b] Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600 036, India
[c] Nizhny Novgorod State Technical University, n.a. R.E. Alekseev, Russia
[d] Marine Systems Institute, Tallinn University of Technology, Akadeemia Rd. 15A, 12618 Tallinn, Estonia

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ABSTRACT

Experimental studies on tsunami are carried out since many years, most of them by generating solitary waves with a piston type wave maker. However, today it is more and more appreciated that these kinds of waves actually do not represent a real tsunami very well, as particularly for the shallow waters at the coast the wave length becomes comparably far too short. Recently new generation methods for scaled down real tsunami experiments were suggested, as it was doubted that sufficiently long waves could be generated with a classical wave maker. The present paper shall disprove these arguments by providing results of a study carried out in the Large Wave Flume (Großer Wellenkanal, GWK), where waves of periods between 30 s and more than 100 s at 1 m water depth were successfully generated with a piston type wave maker. Results for elongated solitary waves, trough led N-waves and real tsunami records as a combination of a different number of general solitons (sech^2 waves) are presented. Finally, the requirements and limitations to bring a "real" tsunami into the laboratory are discussed.

1. Introduction

In the last decade after the catastrophic 2004 Indian Ocean tsunami and several other devastating tsunamis (e.g. Samoa 2009, Chile 2010, Tohoku 2011), several studies on tsunami events in near shore areas and their impact on beaches and coastal structures have been performed experimentally and numerically. However, notwithstanding great progress in tsunami science achieved in recent years, there are still some gaps in understanding the wave behavior at the coast and in the coastal zone. In particular, one of the major questions is the description of tsunami flow, when it propagates over the land carrying mud, sand, stones, pieces of wood and structures, etc. The description of such multiphase flow is a very complicated mathematical and numerical task and physical model tests under controlled boundary conditions can help to better understand the underlying processes and to provide data for the calibration and validation of numerical models.

There have been lots of experimental studies on tsunamis, where special wave shapes, such as solitary waves (breaking and non-breaking), elongated solitary waves, sine waves and N-waves have been investigated (Synolakis, 1990; Li and Raichlen, 2001; 2002; 2003; Chang et al., 2009; Charvet et al., 2013; Goseberg et al., 2013; Sælevik et al., 2013 among many others). The large interest in particular on solitary waves might have two major reasons: (i) these waves have a sound mathematical background (solitary wave theory) and (ii) these waves can be quite easily generated in a flume. However, as shown by Madsen et al. (2008) solitary waves do not represent tsunamis, which are significantly longer and less steep than solitons. Therefore Madsen et al. (2008) suggest to break with the solitary wave paradigm and to use field measurements for studying tsunami waves.

The major challenge for experimental studies of tsunami is the proper scaling of nonlinearity (H/d) and dispersion $(d/L)^2$ and it has been reported that most of the existing testing facilities with piston type wave makers would fail to generate these very long period waves. Therefore, recently some other 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, the results of the studies have shown that there are still several challenges to meet using these new kind of techniques. In particular it seems to be difficult to generate stable waves from the very beginning, as due to the generation methods of pumping or pushing/sucking water through an inlet the region close to the wave maker may suffer from high turbulence levels, breaking waves or compressed air-water phases. If the hydrodynamics are not well defined at the point of generation the interpretation and use of these studies becomes complicated as e.g. (i) even if the water surface elevation at the point of interest (e.g. toe of a slope at the end of the flume) looks reasonable there will always be remaining doubts about a proper representation of the total hydrodynamics and (ii) the data might not be suitable for the validation of numerical models as the essential definition of well-defined boundary conditions is difficult. Further, the new generation techniques have been installed in rather

* Corresponding author. Tel.: +49 511 762 9223.
E-mail address: schimmels@fzk-nth.de (S. Schimmels).

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short or even bended flumes, precluding lots of investigations e.g. at natural shores, which are usually very mildly sloped.

Rossetto et al. (2011) concluded that none of the existing large scale testing facilities, which are usually equipped with a piston type wave maker of reasonable stroke in order to generate large, but comparably short (wind driven) waves, will be able "to produce long period or trough-led waves", with periods O(100 s). The Large Wave Flume (Großer Wellenkanal, GWK) is one of the mentioned facilities and we felt motivated to check the validity of this statement, as such tests in fact have never been tried out before. The present paper will present the methodology and results of a feasibility study to use GWK for generating long period regular waves, elongated solitary waves, trough-led N-waves and scaled down "real" tsunami waves based on two of a very few of existing field measurements. The given examples were rather at the limit of the 4 m stroke wave maker and at the end some general considerations about the limitations of long wave generation using a piston type wave maker are given.

2. Experimental setup

The Large Wave Flume (Großer Wellenkanal, GWK) is about 300 m long, 5 m wide and 7 m deep and usually used for large scale studies in coastal or maritime engineering. The piston type wave maker with 4 m stroke can generate wave heights of up to 2 m at typical periods between 3 s and 8 s and water depths between 4 m and 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 = 50 m, 51.9 m, 55.2 m, 60 m, 225 m, 230 m, 235 m and 245.33 m off the wave maker. At the end of the flume was a 1:6 sloped asphalt dike with the dike toe at x = 251.5 m. Fig. 1 shows a sketch of the experimental setup.

Most of the generated waves in this study had a period of about 100 s, corresponding to a typical earthquake tsunami period of 1000 s on a 1:100 scale. With the present water depth and the 4 m stroke limit of the wave maker the maximum achievable wave heights were (only) about 6 cm, corresponding to a reasonable height of 6 m in nature on the 1:100 scale.

It should be noted that due to the limited water depth of 1 m in terms of usual GWK conditions, the 5 m to 6 m long gauges were operating at their edges, where they become more non-linear and susceptible to measurement uncertainties, which is particularly crucial when dealing with such small wave heights. Therefore the gauges were thoroughly calibrated for the new water depth prior to the experiments and additionally a very well validated numerical model (e.g. Fernández et al., 2013, 2014; Hildebrandt et al., 2013; Sriram et al., 2006, 2007) based on fully non-linear potential flow theory (FNPT) has been applied to verify the results, which is discussed in more detail in Sriram et al. (2015). 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 et al.,2010; Sriram and Ma, 2012). As the back side of the wave board in GWK is dry this crucial requirement can be easily verified and it could be proven that the actual leakage is marginal.

3. Methodology of generation

The first and most important issue to be addressed is how a tsunami is represented best in order to investigate its transformation and impact at the coast. Traditionally the solitary wave theory has been used for tsunami studies, where the temporal evolution of the water surface elevation $\eta(t)$ is described by

$$\eta(t) = H\text{sech}^2(kc(t-t_0)) \quad (1)$$

with

H: wave height
$k = \sqrt{\frac{3H}{4d^3}}$: wave number
d: water depth
$c = \sqrt{g(d+H)}$: wave celerity
g: gravitational acceleration
t_0: time shift

Solitary waves are surely favorable in terms of that they have a sound theoretical background, satisfying the Korteweg de Vries equation under the assumption that nonlinearity $\varepsilon = H/d$ and dispersion ($\mu^2 = (d/L)^2$) are in balance, and over constant water depth they are stable non-periodic (transient) wave forms, comparable to a tsunami. However, Madsen et al. (2008) demonstrated that solitary waves actually do not represent a tsunami very well, not at least because due to the balance of ε and μ^2 their period and length depends on the water depth and solitary waves are unrealistically short in small water depth near the coast.

Therefore for the present study a more generic approach was applied by combining several solitons (sech^2-waves) as suggested by Chan and Liu (2012):

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

where

N: total number of solitons
H_i: wave height of soliton i
$\omega_i = 2\pi/T_i$: cyclic frequency of soliton i
T_i: period of soliton i
t_i: time shift of soliton i
t_0: time shift of whole wave

This generic approach covers the classical solitary wave for $N = 1$ and $\omega_i = kc$ with k and c according to (1) as well as elongated solitons

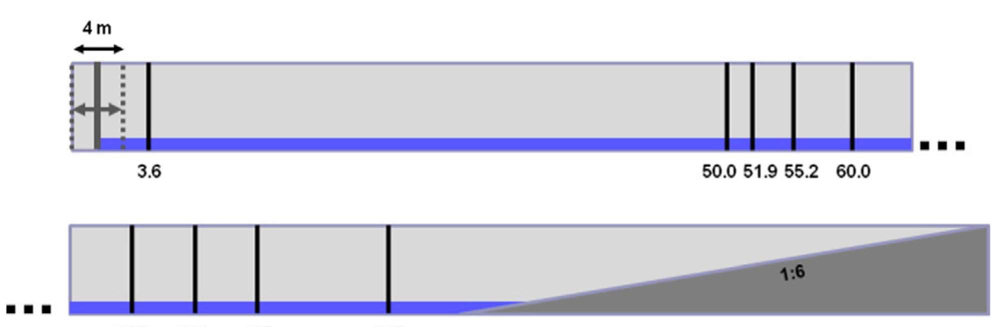

Fig. 1. Experimental setup for tsunami generation tests in GWK.