

ERASMUS MUNDUS MSC PROGRAMME

COASTAL AND MARINE ENGINEERING AND MANAGEMENT
CoMEM

THE EFFECTS OF GEOMETRY ON LANDSLIDE GENERATED TSUNAMIS

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June 2010
University of Southampton

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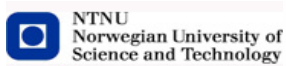
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SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

THE EFFECTS OF GEOMETRY ON LANDSLIDE GENERATED TSUNAMIS

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A dissertation submitted in partial fulfilment of the degree of MSc. in Coastal and Marine
Engineering and Management by instructional course.

June 2010

Summary

Landslide generated Tsunamis are classified as a type of impulse waves. Several parameters including the geometry of the reservoir affect the behavior of impulse waves. The effects of geometry on impulse wave parameters are not yet fully understood.

In order to investigate the effects of geometry on landslide generated impulse waves a total of 168 experiments were conducted in a wave basin of 2.00 m wide and 2.10 m long with a smooth bottom. The water level was kept constant at 0.10 m throughout the experiments. A block model has been used to simulate the landslides.

Experiments were performed in a wave channel, a wave basin (at two different locations) and five diverging reservoir geometries with side angles of 15°, 30°, 45°, 60° and 75°. Plexiglass sheets at different angles were laterally placed inside the basin in order to achieve the desired geometries.

The results of this study indicate that geometry of the reservoir affects wave parameters such as relative wave height, relative wave amplitude, relative wave period, relative wave height decay, and relative wave amplitude decay.

It was found that relative wave height at the wave generation zone corresponding to the wave channel and the wave basin are identical. Wave parameters corresponding to the wave channel are larger than in the wave basin.

Results of this project show a good agreement with Huber (1980) which implies that relative wave height in the slide impact zone for 2D and 3D deviates a little. It was observed that wave parameters corresponding to geometries with reservoir side angles larger than 45° follow a similar trend in the wave basin.

ACKNOWLEDGEMENTS

I would like to offer my appreciation to my thesis supervisor Doctor Valentin Heller, at the University of Southampton, for his substantial contribution in the physical model set ups and experiments, and the resulting works.

I would also want to thank Hydraulics Laboratory staffs who assist me in experimental set up and utilizing the equipments throughout the project.

Appreciation also goes to the CoMEM coordinators at TU Delft professor M. J. Stive and here at SOTON professor R. J. Nicholls.

Also my sincere thanks go to CoMEM administrative committee Ms. Mariette van Tilburg, Ms. Madelon Burgmeijer and Ms. Lenie Wasmus at TU Delft and Ms. Jacqui Graham at SOTON for all their assistance and attention during the past eighteen months.

My sincere and immense appreciations also go to my family; dear Sima, Pedari and Mahan, for all their encouragements and financial and emotional support throughout my studies.

All my CoMEM colleagues, especially D. D. Dowding, B. Narayana, A. Wojtanowicz, J. Haza, S.X. Tay and H. D. Trinh are specially appreciated for their offers of companionship and caring which have added more values to my life during my two years of postgraduate studies.

I would like to give my special thanks to Miss S. J. Marshman for her companionship, patience, and assistance.

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List of Abbreviations

CEM	Coastal Engineering Manual
LDS	Laser Distance Sensor
PIV	Particle Image Velocity
RSA	Reservoir Side Angle
WCHL	Western Canada Hydraulics Laboratories

List of Symbols

a	[L]	wave amplitude
a_M	[L]	maximum wave amplitude
b	[L]	slide or channel width
c	[LT ⁻¹]	wave celerity
d_g	[L]	grain diameter
D	[-]	relative slide density
D_g	[-]	relative grain diameter
F	[-]	slide Froude number
F_1	[-]	slide Froude number = 1.34 (± 0.04)
F_2	[-]	slide Froude number = 1.74 (± 0.07)
G	[LT ⁻²]	gravitational acceleration
h	[L]	still water depth
H	[L]	wave height
H_M	[m]	maximum wave height

j	[-]	number of governing dimensionless parameters
l_s	[L]	slide length
L	[L]	wave length
L_M	[L]	wave length corresponding to a_M or H_M
m	[-]	number of independent governing parameters
m_s	[M]	slide mass
M	[-]	relative slide mass
n	[-]	bulk slide porosity
o	[-]	number of fundamental dimensions
P	[-]	impulse product parameter
r	[L]	radial distance
s	[]	slide thickness
S	[-]	relative slide thickness
t_s	[T]	time of underwater landslide motion
T	[T]	wave period
T_M	[]	wave period of a_M or H_M
T_r	[-]	relative time
T_s	[-]	relative time of underwater landslide motion
V	[-]	relative slide volume
V_s	[LT ⁻¹]	slide impact velocity
V_{sl}	[LT ⁻¹]	slide impact velocity = 1.33 m/s ($\pm$ 0.04)

V_{s2}	$[LT^{-1}]$	slide impact velocity = 1.75 m/s (± 0.07)
V_s	$[L^3]$	bulk slide volume
V_g	$[L^3]$	grain slide volume
x	$[L]$	streamwise co-ordinate
X	$[-]$	relative streamwise distance
z	$[L]$	vertical co-ordinate
α	$[^\circ]$	slide impact angle
θ	$[^\circ]$	reservoir side angle
γ	$[^\circ]$	wave propagation angle
η	$[^\circ]$	water surface displacement
Π	$[-]$	governing dimensionless parameters
ρ_s	$[ML^{-3}]$	slide density
ρ_g	$[ML^{-3}]$	grain density
ρ_w	$[ML^{-3}]$	water density
ϕ	$[^\circ]$	slide front angle

Glossary of Terms

2D	two-dimensional (in a wave channel)
3D	three-dimensional (in a wave basin)
a_M/h	maximum relative wave amplitude
$a(x)/h$	relative wave amplitude decay in 2D
$a(r)/h$	relative wave amplitude decay in 3D
H_M/h	maximum relative wave height
$H(x)/h$	relative wave height decay in 2D
$H(r)/h$	relative wave height decay in 3D

1 Introduction

1.1 RESEARCH BACKGROUND

Tsunamis are classified as nonlinear gravity water waves caused by displacement of volume of a body of water. Tsunamis may occur in open oceans, bays, fjords, lakes. These water waves are categorised as impulse waves and can be generated by earthquakes, landslides, underwater explosions, volcanic eruptions, snow avalanches and other disturbance above or below water surface (Huber & Hager, 1997; Heller, 2008, Heller et al., 2009).

Landslides are the second most common triggers for causing tsunamis after earthquakes (Dudley & Lee, 1998). Compare to seismic tsunamis landslides generated tsunamis may be larger but due to the fast decay these waves, are usually considered as a local phenomenon and not a global incident (Heller, 2008; Heller & Hager, 2010).

Generation mechanism of landslide induced tsunamis depends on initial position of the landslide relative to still water level (Figure 1.1). From this point of view landslides are classified as *submarine (underwater)*, *partially submerged* or *subaerial* landslides. Subaerial landslides often generate much larger waves compare to the other two (Heller, 2008a).

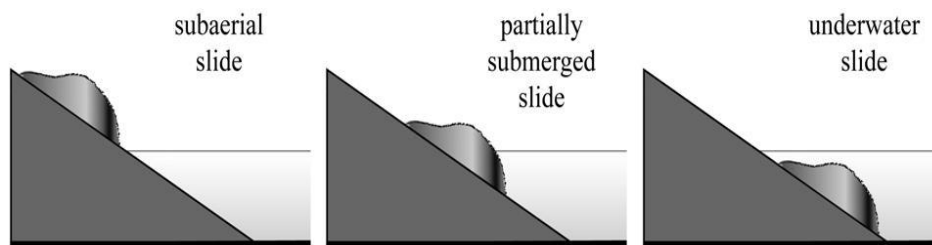


Figure 1.1 Impulse wave generation categories (Heller, 2008)

One of the most destructive landslide generated tsunamis was observed in 1959 in Lituya Bay, Alaska, when a subaerial landslide of $31 \times 10^3 \text{ m}^3$ volume, which was triggered by an earthquake, slid into the bay and lead to a tsunami. The wave with the highest ever recorded wave run-up of 254 meters on the opposite shore of the bay propagated towards Pacific Ocean (Fritz et al., 2009).

Another lethal instance of landslide generated tsunamis took place in 1963 in northern Italy. A landslide of $270 \times 10^3 \text{ m}^3$ volume impacted the water impounded by Vajont dam, which was a newly constructed concrete arch dam, and the overtopping of the 300 m height

impulse wave destroyed the town of Longarone, located behind the dam (the overtopping was 70 m) (Panizzo et al., 2005a). Heller (2008a) has summarised some of historical cases of landslide generated tsunamis.

Although not all impulse waves caused by landslides are as destructive as the mentioned cases but where ever tsunamis occur, the waves propagate at high speed to a far distance from the slide impact point with little energy dissipation (compared to e.g. wind waves) hence this can lead to devastation in coastal regions, shoreline damages, dam overtopping in case of artificial reservoirs, downstream flooding and generally financial losses and even human perishes (Dudley & Lee, 1998; Heller, 2008).

Certain environments such as mountainous regions are more vulnerable to landslide generated tsunamis because of their steep valley sides and unstable and steep slopes (e.g. Alpine regions) (Heller et al., 2009).

A high risk environments hazard forecasting is essential but at present in order to prevent major casualties and reduce consequences of such catastrophes mainly passive methods can be applied. These strategies are such as evacuation, freeboard control, water level draw-down in artificial reservoirs and blasting of possible slides. To perform any of the aforementioned operations precise information on landslides physics and wave features is necessary. Also in order to build and maintain coastal and hydraulic structures (e.g. dams) effects of these waves on structures or the shoreline should be investigated. To calculate these forces wave height H , wave amplitude a , and wave length L at specific locations of the reservoir are required (Müller, 1995; Heller et al., 2009).

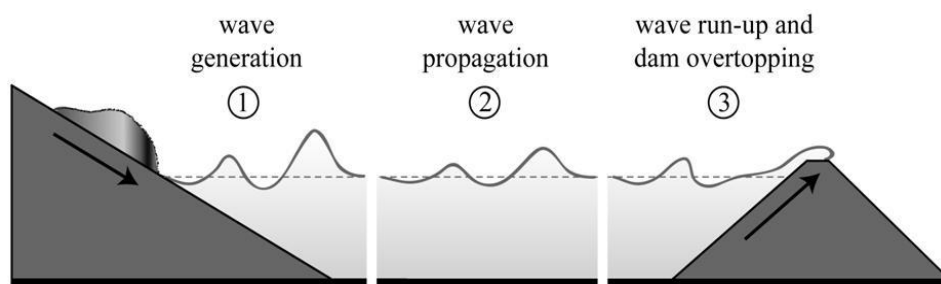


Figure 1.2 the three phases of an impulse wave above a horizontal reservoir bed (Heller et al., 2009)

Figure 1.2 shows the three phases of development of an impulse wave above a horizontal reservoir bed: (1) slide impact with the wave generation, this zone is referred to as wave generation zone hereafter, (2) wave propagation with the wave transformation (namely

wave propagation zone) and (3) impact and run-up of the impulse wave with the load transfer to a dam and overtopping of the dam (Heller et al., 2009).

Several parameters are involved in generation and propagation of landslide induced tsunamis. These waves are highly non-linear and therefore the identification of each parameter and predicting features of the wave is a complicated process. Types and features of the landslide and topology and geometry of the reservoir in which impulse wave occurs affect the characteristics of the waves (Huber & Hager, 1997; Heller, 2008).

Features of tsunami type waves can be predicted by applying five different strategies: specific prototype studies, numerical simulations, prediction based on field data, analytical calculations, and general model studies (Heller & Hager, 2010).

Various physical and numerical simulations have been performed since the mid-nineteenth century (started from the study of Russell (1837) using a block model in a prismatic wave channel) in order to examine governing parameters of generating impulse waves. Several empirical equations have been developed as the subject of these studies (Heller, 2008).

Shape and dimensions of the basin highly affect impulse wave propagation mechanism and affects waves parameters such as wave height, wave length, wave period etc. This was denoted by Camfield (1980) and emphasised by Chang et al. (1979) and Heller et al. (2009) amongst others.

Studies on landslide generated impulse waves have mostly been conducted in either wave channels (2D), where the waves propagate along the channel axis and measurements are in two dimensions, or in wave basins (3D), in which waves can propagate radially freely and measurements are conducted in three dimensions. However in reality geometries often remarkably differ from these two extreme cases (Figure 1.4).

Studying effects of geometry on landslide generated impulse waves have been subject of some numerical investigations yet it is not completely understood how different geometries may lead to different behaviours of impulse waves. At present waves parameters (in case of granular slide models) in general geometries can just be estimated by using formulas derived from studies on the two extreme geometries (2D and 3D). This area has been identified as a research gap by Heller et al. (2009). To investigate the effects of

geometry on subaerial generated tsunamis Kinnear (2009) conducted a number of physical experiments at University of Southampton. The present project is been defined to improve the which was used by Kinnear (2009) in order to conduct the experiments, and also to expand the knowledge in this area.



Figure 1.3 Display of wave propagation in general geometries (source: Google Earth)

1.2 AIMS AND OBJECTIVES

In order to obtain a better understanding on effects of geometry on landslide generated tsunamis the present master thesis was conducted in Hydraulics laboratory of School of Civil Engineering and Environment of University of Southampton.

The objectives of this research are defined as follows:

- What is the effect of the reservoir geometry on landslide generated tsunami characteristics?
- How can the results in general geometries be related to 2D (wave channel) results from previous studies?

- How do the new results agree with existing formulas?

The experiments are carried out in a rectangular wave basin based on Froude similitude and a block model is used to simulate the landslide. To achieve different geometries lateral walls built of plexiglass are fixed inside the basin with different side angles (θ). The layout of which is shown in Figure 1.4. In this project other than the two extreme cases (2D and 3D) six further geometries are investigated. Five of which includes different side angles and one case which does not involve installing any lateral walls. This geometry is called "3D corner" herein. This case is specifically defined in order to study behaviour of impulse waves which are generated by landslides in close proximity to the dams (e.g. K  thai reservoir, Austria) (Figure 1.3).

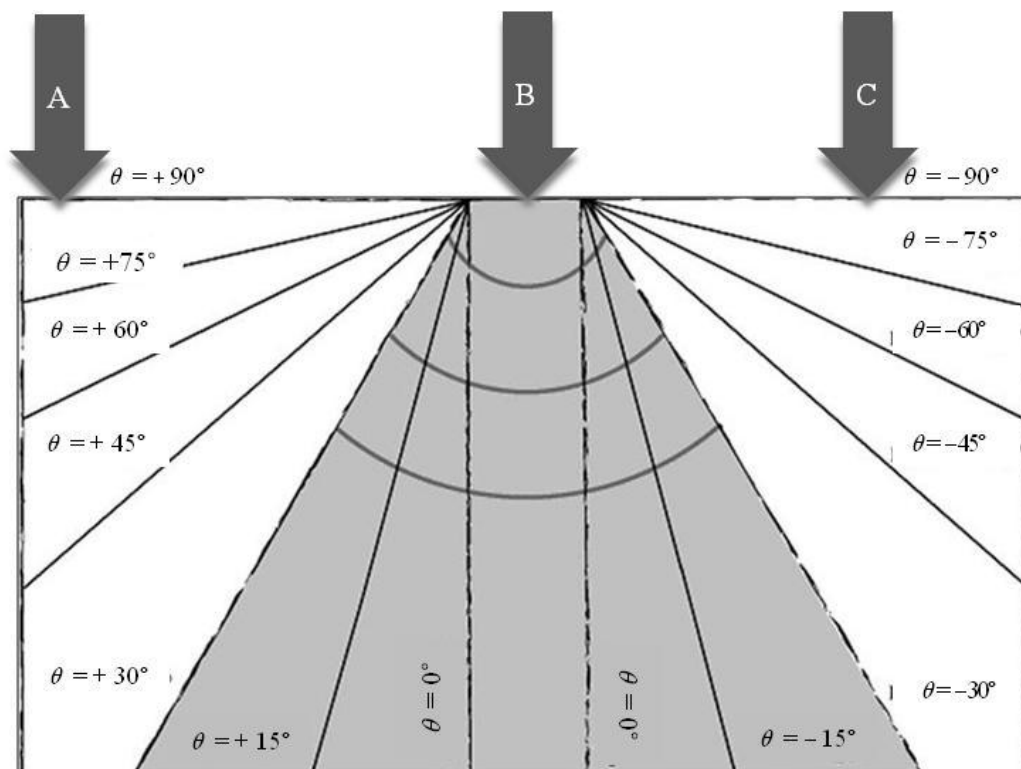


Figure 1.4 Reservoir Geometries: θ identifies reservoir side angle. A, B, and C show the three slide release positions which are studied throughout the experiments (altered from Kinnear (2009)).

This study concentrates on subaerial landslide induced tsunamis. In this project all governing parameters such as still water depth, slide volume, etc. is constant with the exception of geometry of the basin. Within each of the geometries only slide impact velocity is systematically changed.

1.3 THESIS OUTLINE

The rest of this report is structured as follows:

The second chapter of this project *Literature Review* contains a brief review on previous studies on subaerial landslide generated impulse waves. The main focus in this part is on physical modelling studies and mainly those which have investigated the different geometries or compared the two extreme cases.

The third chapter *Methodology* presents a brief explanation on scale effects and Froude similitude and describes the steps of conducting the experiments. This chapter also explains the different equipments and tools which are utilized for conducting the experiments.

In the forth chapter *Experimental Results* the procedure of processing the data is described and the initial results of the experiments are introduced. In this chapter the main focus is on comparing different geometries together. Different parameters such as relative wave height H/h , relative wave amplitude a/h and impact velocities can be obtained from figures and tables in chapter four.

The report continues with *Discussion and Analysis of Results* in chapter five. In this section the results from the experiments are analysed and compared with achievements from previous researches. In order to develop a general equation for measuring wave decay which is a function of basin side angle a set of initial calculations is presented in this section.

The last chapter *Conclusions and Recommendations* discusses the possible strategies to improve the physical model and the process of conducting the experiments. Potential areas for further research are also introduces in this part.

2 Literature review

2.1 INTRODUCTION

Landslide generated tsunamis are classified as nonlinear gravity water waves (Heller, 2008). Occurrence of these impulse waves can lead to some of the most destructive natural catastrophes (Pannizo et al., 2005b; Fritz et al., 2009; Huber & Hager, 1997). In order to decrease the amount of damage from this phenomenon on the structures and properties and the number of human losses the characteristics of these waves should be investigated. As a reason studying the behaviour of these impulse waves and their effects on the structures and shorelines are of vital interest. Therefore several variables are involved in generation and propagation of impulse waves. Since mid- nineteenth century various studies in form of physical or numerical modelling or analytical studies have been carried out in order to classify and characterize these waves. Because of complication of physics of landslide generated impulse waves still not all influential parameters are fully recognized.

In this chapter first different types of water waves and nonlinear wave theories are briefly discussed. Governing and dimensionless parameters of impulse waves are next introduced. This chapter ends with presenting a short overview of the technical literature in this area.

2.2 WATER WAVES

"Impulse waves include tsunamis generated in lakes or reservoirs and they belong to the group of surface gravity water waves" (Heller, 2008).

Hereafter different terms of the above statement are briefly discussed.

Any displacement of the water surface from its equilibrium state can be identified as water waves. In this project only gravity surface water waves are discussed (excluding e.g. capillary water waves). Water waves can be classified as *oscillatory* or *translatory* wave, from physical point of view. There is in the average no mass fluid transport for a pure oscillatory wave. On the other hand a pure translatory wave involves mass fluid transport in the direction of motion. Most of the times waves are a combination of both mentioned types (Le Méhauté, 1976 and Heller, 2008). Water waves can also be categorised as *shallow* (e.g. earthquake generated tsunamis), *intermediate*, or *deep* (e.g. wind waves) water waves. Shallow water waves are those waves with wave length L over water depth h is less than 2,

intermediate water waves are the waves with $2 \leq L/h \leq 20$, deep water waves are defined as waves with $L/h < 2$ (Figure 2.1).

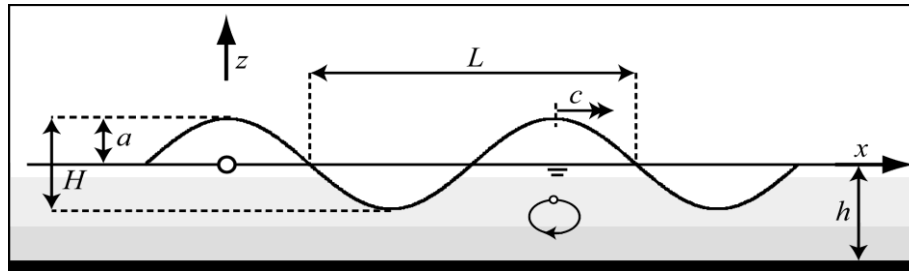


Figure 2.1 Basic wave parameters illustrated for a pure oscillatory shallow water sinusoidal wave with closed particles orbits. With h indicating still water depth, H wave height, a wave amplitude, L wave length and c wave celerity (Heller, 2008).

Other than the mentioned classifications, water waves can be categorized as *linear* and *non-linear* waves from mathematical aspect. Linear wave theory which is also known as Airy theory (after Airy, 1845) and small amplitude wave theory. This theory is called linear because terms are of higher order such as $(H/L)^2$ neglected in calculation of the relevant forces and parameters. In case of linear wave theory, wave profile is characterised by a sinusoidal shape and motion of the particles is oscillatory. Linear wave theory can be applied for shallow, intermediate and deep water (for more information on Linear wave theory see Dean & Dalrymple, 1991; Heller, 2008) (Figure 2.1). Linear wave theory is often applied in practice because of its simplicity and also because it is valid over a high range of initial criteria (Heller, 2008).

The general range of validity for linear wave theory is $H/h < 0.03$ and $H/L < 0.006$ (Dean & Dalrymple, 1991).

Landslide generated impulse waves are typically highly nonlinear in the range of intermediate to shallow water waves with considerable fluid mass transport (Heller, 2008).

Different types of nonlinear waves are characterised by different nonlinear wave theories. Herein four types of nonlinear waves which are more likely to conclude landslide generated impulse waves, are introduced; Stokes, Cnoidal, Solitary and Bore waves.

Stokes Waves are deep to intermediate water waves. Like linear waves, these waves also follow a periodic trend but they have steeper crests and flatter troughs as compare to linear waves. Water particles do not have a pure oscillatory motion and as a result a slight fluid mass transport occurs (Figure 2.2) (Dean & Dalrymple, 1991; CEM, 2008; Heller, 2008).

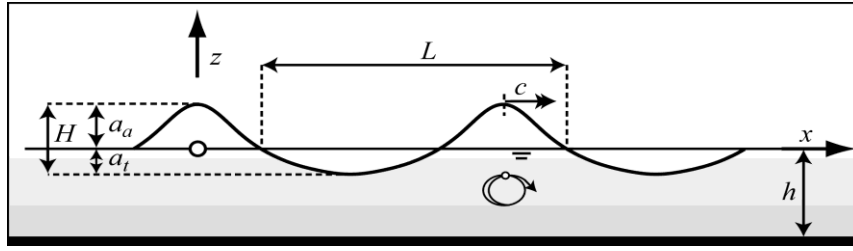


Figure 2.2 Stokes wave profile with the basic parameters and open particle orbits (Heller, 2008).

Cnoidal Waves, which include waves such as wind waves in shallow water, have first been identified by Korteweg and de Vries (1895). Cnoidal waves theory spans between linear wave theory and Solitary wave theory ($T \rightarrow \infty$) (T indicating wave period). These periodic waves can be seen in intermediate to shallow water. Water particles move in open orbits and fluid mass transport occurs (Figure 2.3).

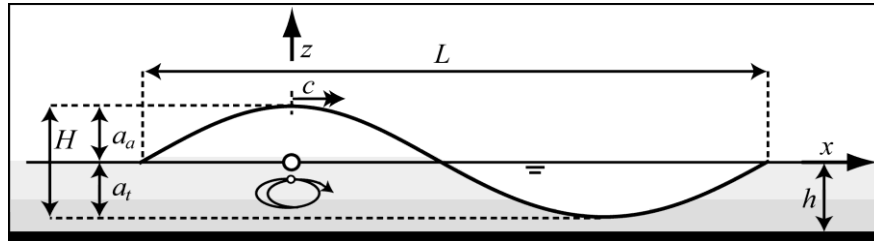


Figure 2.3 Cnoidal wave profile with the basic parameters and open particle orbits (Heller, 2008).

Solitary Waves are characterised by only a water surface elevation and no depression, in other word these waves do not have troughs. Particle movement is horizontally and as a result considerable fluid mass transport occurs in this case (Figure 2.4). A pure solitary wave can rarely be found in nature, however landslide generated tsunamis are best characterise by applying this theory (Dean & Dalrymple, 1991; CEM, 2008; Heller, 2008).

Wave celerity of solitary waves is calculated from equation (2.1) which was denoted by Russell (1837) throughout his studies on solitary waves. This has been studied and confirmed by a number of later investigators e.g. Noda (1970) or Panizzo et al. (2002) amongst others (Dean & Dalrymple, 1991; Heller, 2008).

$$c = (g(h + a))^{0.5} \quad (2.1)$$

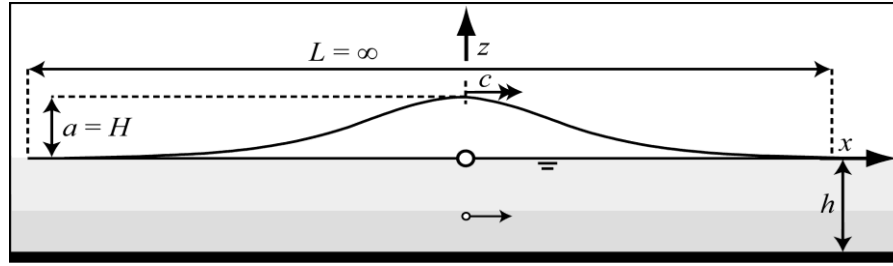


Figure 2.4 Solitary wave profile with basic parameters and horizontal particles movement (Heller, 2008)

Bore Waves are induced when amplitude of solitary wave exceeds the breaking limit. Bore waves can be found in shallow waters and are characterised by steep front and sloping back (Figure 2.5). Mass fluid transport occurs in case of bore waves because of horizontal particle movement (CEM, 2008; Heller, 2008).

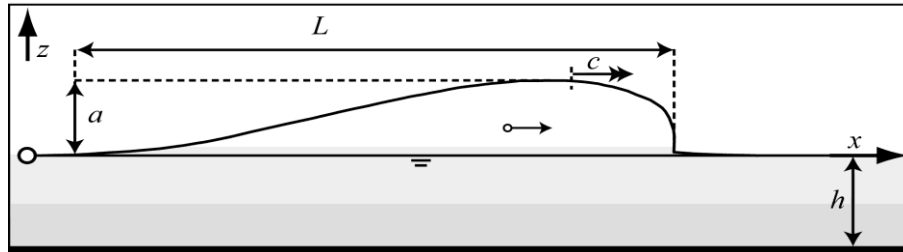


Figure 2.5 Bore wave profile with the basic parameters and horizontal particle movement (Heller, 2008).

2.3 WAVE PARAMETERS

2.3.1 GOVERNING PARAMETERS

In order to investigate behaviour of landslide generated tsunamis, waves features such as wave height H , wave amplitude a , maximum wave height H_M , maximum wave amplitude a_M , and the corresponding wave period T_M need to be measured. Characteristics of the landslide and the environment in which the landslide occurs, affect the mentioned waves parameters. Hence several studies have been carried out in order to identify the governing parameters which mainly affect impulse wave characteristics.

Fritz (2002), Zweifel (2004) and Heller (2007) amongst others studied effects of same set of parameters on waves generated by granular landslides (Figure 2.7). These governing parameters were confirmed by Heller et al. (2009) and are accounted as governing parameters for this project.

According to Heller et al. (2009) the parameters which affect properties of the impulse waves are listed as follow:

- Slide impact velocity V_s
- Bulk slide volume V_s
- Slide thickness S
- Slide or reservoir width b
- Bulk slide density ρ_s
- Bulk slide porosity n
- Slide impact angle α
- Still water depth h

These parameters are mainly indicating the properties of the landslide except for the still water depth and the slide impact angle.

Overall same governing parameters can be applied for both block and granular slide types. However, some parameters such as bulk slide volume and bulk slide density are defined differently in case of granular slides than solid block (Figure 2.6).

Heller et al. (2009) presented the conversion equations (2.2) and (2.3) which declare the difference between the two slide model types. This difference should be allowed in formulas which calculate characteristics of impulse waves.

$$\rho_s = (1 - n)\rho_g \quad (2.2)$$

$$V_s = V_g/(1 - n) \quad (2.3)$$

Slingerland and Voight (1979) compared the two slide model types and found that the maximum wave amplitude may be four times higher when it is generated by solid blocks instead of granular materials. Zweifel (2004) conducted a set of tests with limited variations of the governing parameters came to a similar conclusion. Zweifel (2004) observed that for Froude numbers less than 3, in tests with identical governing parameters block models can generate up to seven times higher maximum wave amplitudes of than granular slide models.

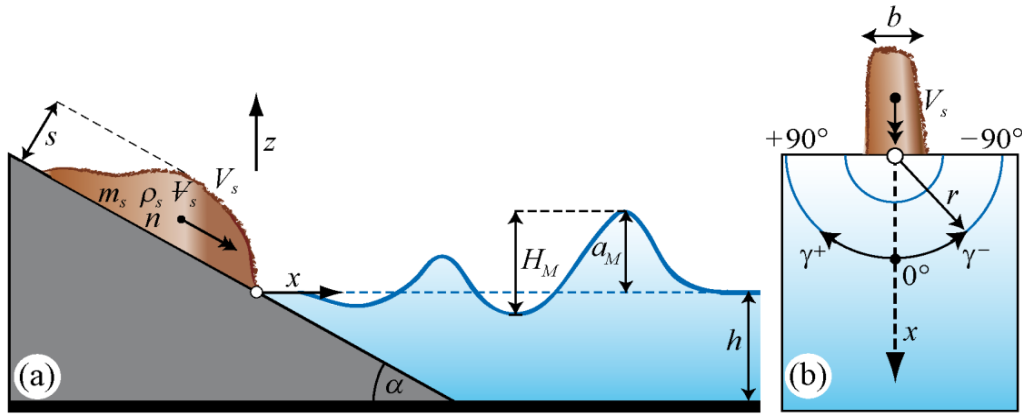


Figure 2.6 Governing parameters on impulse waves: (a) 2D; (b) 3D (Heller et al., 2009).

The mentioned governing parameters except for h , α , and V_s may vary from slides release position to its impact point (only in case of granular slide) and they may further change after the slide hits the water. Hence landslides governing parameters should not be measured at its original location. These parameters are defined at the slide impact zone (the intersection of still water level and slides slope; $x = 0$).

Heller et al. (2009) declare that effects of parameters such as landslide length l_s and slide front angle φ are negligible on impulse wave characteristics.

A further parameter, time of underwater slide motion t_s , was introduced by Walder et al. (2003) based on studies of Watts (1998) on underwater landslides. This parameter indicating the splash zones dynamics was recognized in studies of Pannizo et al. (2005a) and submarine landslide studies of Ataie-Ashtiani and Nik-Khah (2008). However this parameter has been excluded in most of the studies on landslide generated impulse waves such as studies of Huber and Hager (1997), Fritz et al. (2004) and Heller (2008). Heller et al. (2009) note the difficulties in calculating this parameter. Pannizo et al. (2005a) deduced a formula which calculates t_s as a function of other governing parameters. This parameter is not considered in this study.

As the wave travels further from the impact point the wave height decreases due to energy dissipation. Physically the effect of viscosity results in the dissipation of energy that is finally transferred into heat and lead to wave height damping (Debanath, 1994).

Wave properties in 3D cases can be calculated accounting same governing parameters as 2D. However since experiments in wave channels neglect the spatial propagation of the waves and they underestimate the wave height damping effect (Huber, 1980; Heller et al., 2009).

Characteristics of impulse waves vary as the wave propagates in a horizontal channel or wave basin as a function of following parameters:

- Streamwise distance x
- Radial distance r
- Wave propagation angle γ

Other than the mentioned parameters the shape of the reservoir has a significant effect on propagation of impulse waves (Camfield, 1980). Phenomena such as shoaling, diffraction, refraction, reflection and constriction may occur. Occurrence of all depends on the geometry and bathymetry of the reservoir. In order to study the effects of geometry on tsunamis characteristics a new governing parameter is defined in this study namely the reservoir side angle θ (Figure 1.4). This parameter was first introduced in the study of Kinnear (2009) as *RSA*.

2.3.2 DIMENSIONLESS PARAMETERS

Other than governing parameters, dimensionless parameters are often used in the previous studies. Applying dimensionless parameters is especially common in physical studies. Advantages of using dimensionless parameters are simplification of physical work by reducing number of variables also a certain parameter would remain constant in all experiments and can be used for checking the accuracy of experiments. Dimensionless parameters do not change with scale ratio so they can be compared in different experiments (Le Méhauté 1990).

Dimensionless parameters are yield by using dimensional analysis. By using π - theorem of Buckingham (1914), independent governing parameters (q_1 to q_m) of a physical phenomenon may be reduced to ($j = m - o$) governing dimensionless parameters (π_1 to π_j) where o is the number of fundamental dimensions (e.g. length and time) without losing any physical information.

Heller (2008) identifies eight dimensionless parameters applicable in landslide generated impulse waves studies. These parameters are listed as follow:

- Slide Froude number $F = V_s/(gh)^{1/2}$
- Relative slide thickness $S = s/h$

- Relative slide volume $M = D.V$
- Relative streamwise distance $X = x/h$
- Slide impact angle α
- Relative grain diameter $D_g = d_g/h$
- Relative time $T_r = t(g/h)^{1/2}$

Some of these dimensionless parameters such as F and X have been applied in this project.

$$D = \rho_s / \rho_w \quad \text{Relative slide density}$$

$$V = V_s / (bh^2) \quad \text{Relative slide volume}$$

2.4 MODEL INVESTIGATIONS

In this section a brief review of previous studies on landslide generated impulse waves and some of the derived empirical formulas are presented. The main focus is on physical modelling projects.

Figure 2.7 summarizes the physical models studies since 1837, which have investigated influential parameters on impulse wave generation and propagation.

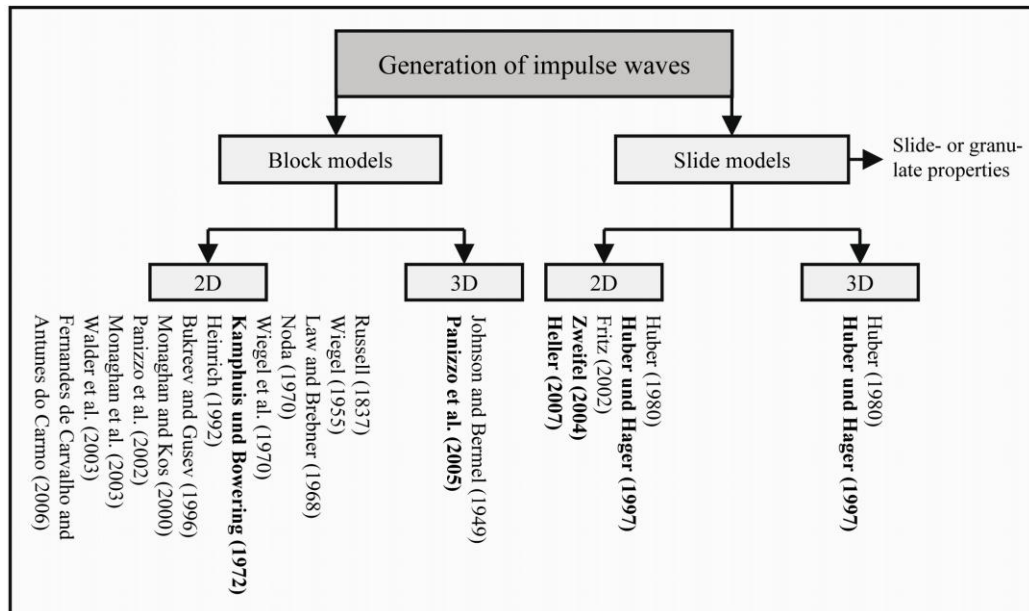


Figure 2.7 Classification of parameter studies of subaerial landslide generated impulse waves based on block or slide models in 2D or 3D (Heller, 2008b).

Most of the previous studies on impulse waves have studied maximum wave height H_M and maximum wave amplitude a_M . But if the opposite shoreline or the structure would be

located in a long distance from the slide impact point, in order to obtain wave features, formulas for the wave decay in terms of distance from slide impact zone is required (Heller 2008b). Also in order to calculate wave run-up and overtopping on the structures other than wave height H and wave amplitude a , values for wave period T are required (Müller, 1995; Heller et al., 2005). The experiments which have included decay of impulse wave parameters are explained in more details in the following sections.

2.4.1 WAVE CHANNEL PHYSICAL EXPERIMENTS

Experiments conducted by Russell (1837) can be considered as the origin of landslide generated impulse wave research. Russell (1837) carried out a set of experiments in a wave channel. He studied parameters of solitary waves which were induced by dropping a box vertically into the water. Russell (1837) measured the initial water displacement volume and celerity of the solitary wave by Eq. (2.1). Several researchers have repeated experiments of Russell (1837).

The primary impulse waves studies were conducted under simplified conditions for example the landslide was modelled by a square box impinging a water body with slide impact angle $\alpha = 90^\circ$ (Heller et al., 2009)

The first 2D block model study which considered more realistic conditions for simulating the slide impact was conducted by Wiegel (1955). A rigid body was released vertically on an incline into the wave channel. Wiegel (1955) observed a more dispersive wave characteristic with increasing the slide density ρ_s .

Noda (1970) performed experiments which lead into wave classification. Noda (1970) considered only wave propagation and classified four wave types as a function of Froude number and relative slide thickness namely the oscillatory, the non- linear transient, the solitary wave, and the bore regions.

Kamphuis and Bowering (1972) conducted experiments in a wave channel of 45 m length and 1 m width using a block model. In order to investigate relevant dimensionless parameters they varied h , α , ϕ , and V_s and measured the relative wave amplitude decay. Kamphuis and Bowering (1972) noted slide Froude number and relative slide volume are the dominant parameters with slide front angle ϕ being negligible. Also they observed that the relative wave height decayed exponentially with the distance from slide impact point (Eq. 2.4).

Walder et al. (2003) performed a set of experiments in a wave channel which curved smoothly from the slide slope to the horizontal bed using a block model simulating an underwater landslide. They varied h , m_s and α in order to investigate impulse wave parameters in wave generation zone. The relative wave amplitude was defined as a function of t_s and V_s . Calculating the parameter underwater landslide motion in this case was based on underwater landslide studies (Watts, 1998; Watts, 2000). In this study scaling analysis based on Euler equations were performed in order to yield different dimensionless parameters.

Huber (1980) conducted about 1150 experiments with granular materials in both wave channel and wave basin. 1000 of these experiments were performed in 2D. Huber (1980) varied the slide impact angle, slide mass, still water depth in order to measure wave heights, wave lengths, the corresponding wave period and wave celerity.

Huber and Hager (1997) reanalysed the results from studies of Huber (1980) and derive Eq. (2.6) for the relative wave height decay. Their finding can be considered as general guidelines for 2D and 3D granular material studies (Heller, 2008b). Huber and Hager (1997) noted that slide impact angle α has a dominant effect on wave height followed by relative slide volume. In their studies effects of still water depth, relative location and relative slide density were found to be inconsiderable.

Fritz (2002) carried out experiments in a wave channel using granular slide model. He used a pneumatic landslide generator which allows varying parameters independently and also gives high test repetition accuracy. Fritz (2002) applied PIV, Particle Image Velocity along the channel axis. He noted Froude velocity has a dominant effect on impulse wave characteristics. The main results were summarised in Fritz et al. (2004) and an equation describing the maximum relative wave amplitude was presented.

Zweifel (2004) continued the studies of Fritz (2002), using the same physical model. His study confirms Eq. (2.8) of Fritz (2002). He included a new governing parameter M which indicates relative slide mass. Studies of Zweifel (2004) lead to Eq. (2.9). Further Zweifel (2004) compared block and granular slide types for a limited number of experiments. He observed that for $F < 3$ block slides generate waves with a_M up to seven times larger than granular slides.

Heller (2008) continued the investigations of Fritz (2002) and Zweifel (2004) by studying effects of slide impact angle and the grain diameter of the granular slide. Heller (2008) found that slide Froude number is highly influential on wave parameters with the

relative slide thickness and relative slide mass having a smaller effect. Heller (2008) identified the maximum relative wave amplitude and the maximum relative wave height are correlated with the impulse product parameter P.

$$P = FS^{1/2}M^{1/4}\{\cos[(6/7)]\alpha\}^{1/2} \quad \text{for } 0.17 \leq P \leq 8.13 \quad (2.4)$$

Where;

F [-] = Slide Froude number

M [-] = Relative slide mass

S [-] = Relative slide thickness

A [°] = Slide impact angle

Equations (2.11) and (2.12) show this relation. Also Heller (2008) derived empirical equations for calculation of relative wave height and amplitude decay (Eq. (2.13) and Eq. (2.14)).

Table 2.1 presents a list of empirical equations which are derived from wave channel experiments and are used for calculating different properties of impulse waves.

Table2-1 wave channel empirical equations

Wave Parameter	Equation	Author(s)	Year	Eq. No.
$H(x)/h$	$\left[F^{0.7} \left(0.31 + 0.2 \log \left\{ S \frac{l_x}{h} \right\} \right) \right] + 0.35 \exp \left(-0.08 \left(\frac{x}{h} \right) \right)$	Kamphuis and Bowering	1972	2.5
$H(x)/h$	$0.88 \sin \alpha \left(\frac{\rho_g}{\rho_w} \right)^{1/4} \left[\frac{V_g}{bh^2} \right]^{1/2} X^{-1/4}$	Huber and Hager	1997	2.6
a_M/h	$(1/4)F^{7/5}S^{4/5}$	Fritz	2002	2.7
a_M/h	$1.32 \left(\frac{t_s}{V} \right)^{-0.68}$	Walder et al.	2003	2.8
a_M/h	$(1/4)FS^{1/2}M^{1/4}$	Zweifel	2004	2.9
$a(x)/h$	$2S^{1/2} \tanh \left[0.25F^{3/2} \left(\frac{M}{X} \right)^{1/2} \right]$	Zweifel et al.	2006	2.10
a_M/h	$(4/9)P^{4/5}$	Heller	2008	2.11
H_M/h	$(5/9)P^{4/5}$	Heller	2008	2.12

Wave Parameter	Equation	Author(s)	Year	Eq. No.
$a(x)/h$	$(3/5)(PX^{-1/3})^{4/5}$	Heller	2008	2.13
$H(x)/h$	$(3/4)(PX^{-1/3})^{4/5}$	Heller	2008	2.14
a_M/h	$(0.398 + 0.076(VF^2)^{1.27}) \left(\frac{t_s}{V}\right)^{-0.26} \left(\frac{l_s}{s}\right)^{-0.125} \left(\frac{x}{h}\right)^{-0.48}$	Ataie- Ashtiani and Nik-Khah	2008	2.15

2.4.2 WAVE BASIN PHYSICAL EXPERIMENTS

Johnson and Bernel (1949) conducted experiments in an axial symmetric wave basin studying relative wave amplitude decay.

Singerland and Voight (1979) repeated experiences of Johnson and Bernel (1949) and found relative wave height decay to be a function of r^{-1} .

Panizzo et al. (2005b) performed experiments in a rectangular wave basin with a block impacting the water at the corner of the basin. By assuming symmetry Panizzo et al. (2005b) similitude landslide generated impulse waves for one quarter of the basin. They considered t_s in their study and derived an equation which calculates t_s as a function of other parameters. Panizzo et al. (2005b) compared the results of their study with outputs of previous studies from both 2D and 3D experiments. Further they derived empirical equations for different wave characteristics (Eq. (2.17) and (2.18)).

Most of the experiments on granular landslides in 3D investigate a specific case. Such as WCHL (1970) modelling the Mica Reservoir in British Columbia with scale of 1:300. Bags of gravel were applied to model the landslide. Davidson and Whalin (1974) modelled Lake of Koocanusa in Montana with a scale of 1:120 where bags of iron were used to model the landslide.

Huber (1980) conducted experiments in 3D considering the same variables as for the 2D case with including wave propagation angle γ . He compared the results of these tests with his 2D results and found that "Near to the impact zone (at $r/h = 5$) the heights of 2D and 3D waves deviate little from each other".

Huber and Hager (1997) reanalysed the study of Huber (1980) and found an empirical equation for wave height damping which is used widely (Eq. (2.16)).

Fritz et al. (2009) conducted a set of experiments in wave channel and wave basin, using granular materials and performing highly accurate methods to model Lituya Bay landslide. They conducted the 2D experiments using PIV and LDS (Laser Distance Sensor) methods. The wave generated by a granulate inflow. The measured relative wave amplitude from these experiments agreed with calculated values using Fritz et al. (2004) empirical formula. They also compared the measured values of this experiment with calculated values using previous empirical formulas.

In 3D Fritz et al. (2009) modelled a 1:400 scale of Lituya Bay. Landslide deposit mapping was concluded, for example, in Lake of Lucerne. The waves were generated by a pneumatic landslide generator and PIV was used for these tests.

Fritz et al. (2009) declared that detailed three dimensional bathymetry and topography survey of Lituya Bay are required be constructed in a physical model for direct comparison.

Table 2.2 presents a list of empirical equations for wave basin which are used in order to calculate different properties of impulse waves.

Table2-2 wave basin empirical equations

Wave Parameter	Equation	Author(s)	Year	Eq. No.
$\log(a_M/h)$	$-1.25 + 0.71 \log \left[(1/2) \left(\frac{V_g}{h^3} \right) \left(\frac{\rho_g}{\rho_w} \right) F^2 \right]$	Slingerland and Voight	1979	2.16
$H(r)/h$	$2.088 (\sin \alpha) \cos^2 \left(\frac{2\gamma}{3} \right) \left(\frac{\rho_g}{\rho_w} \right)^{1/4} \left[\frac{V_g}{bh^2} \right]^{1/2} \left(\frac{r}{h} \right)^{-2/3}$	Huber and Hager	1997	2.17
$H(r)/h$	$0.07 \left(\frac{t_s}{(b_s/h^2)} \right)^{-0.045} (\sin \alpha)^{-0.88} \exp(0.6 \cos \gamma) \left(\frac{r}{h} \right)^{-2/3}$	panizzo et al.	2005(a)	2.18
H_M/h	$0.0924 \left(\frac{t_s}{V} \right)^{-0.3136}$	panizzo et al.	2005(a)	2.19
$H(r)/h$	$(3/2)P^{4/5} \cos^2 \left(\frac{2\gamma}{3} \right) \left(\frac{r}{h} \right)^{-2/3}$	Heller et al.	2009	2.20

2.4.3 GENERAL GEOMETRIES PHYSICAL EXPERIMENTS

Effects of geometry of the basin on impulse wave behaviour have been considered in studies of Chang et al. (1979) and Kinnear (2009).

Chang et al. (1979) conducted experiments using a block model to study the behaviour of solitary waves in a channel of gradually varying width b . The side angle of the channel in this study was 0.019 radians (1.09°).

Chang et al. (1979) compared the measured values for relative wave amplitude with the numerical results from Kortweg de Vries (KdV) equation. Results corresponding to the diverging channel showed good agreement with the prediction from KdV equation; $a \propto b^{-2/3}$. For the linearly converging channel the wave amplitude differs well approximated by $a \propto b^{-1/2}$.

The present study is based on studies of Kinnear (2009). Kinnear (2009) conducted experiments in a wave basin with a constant water depth using a block type slide model. He investigated effects of geometry on different characteristics of impulse waves such as relative wave height, wave amplitude and decay of these parameters. Different geometries were achieved by placing diagonally vertical walls inside the basin with different side angles of 15°, 30°, 45°, 60° and 75°. This study also included experiments in the two extreme cases of 2D (0°) and 3D (90°). Kinnear (2009) concluded that wave height and wave amplitude are affected by geometry of the basin. Also it was postulated that the reservoir geometries investigated in that case could be divided into three different groups based on how does the reservoir geometry effects on wave generation zone.

Other than the physical modelling studies which were briefly discussed in this chapter other methods have been applied to investigate impulse wave behaviour such as numerical modeling studies by Heinrich (1992), Mader (1992), Monaghan and Kos (2000) and mathematical studies by Noda (1970), Iverson and Denlinger (2001).

2.5 SUMMARY

Various parameters are involved in generation and propagation of impulse waves. Ever since mid-nineteenth century different studies were carried out to study impulse waves in wave channel or wave basin using block or granular slide models. Almost all were based on Froude similitude (Section 3.x). Different empirical equations were derived as a function of different set up of each experiment and different combination of governing and dimensionless parameters. Some of the dimensionless parameters are common in most cases such as slide Froude number F and relative slide volume V_s . More studies are required on other parameters such as slide impact angle α and time of underwater slide motion t_s . Outputs of different studies deriving same wave parameters are not completely comparable since the governing

parameters are not identical. Heller (2008) associated this with the measurement of wave features at different relative distances, use of different measurement systems (camera, wave gauges) applying block or granular slide models, experiments in the range of non-negligible scales effects, or the influence of water splash.

An example for this can be seen in Figure 2.8; identical parameters have been measured two experiments conducted in wave basin. The results are not identical however.

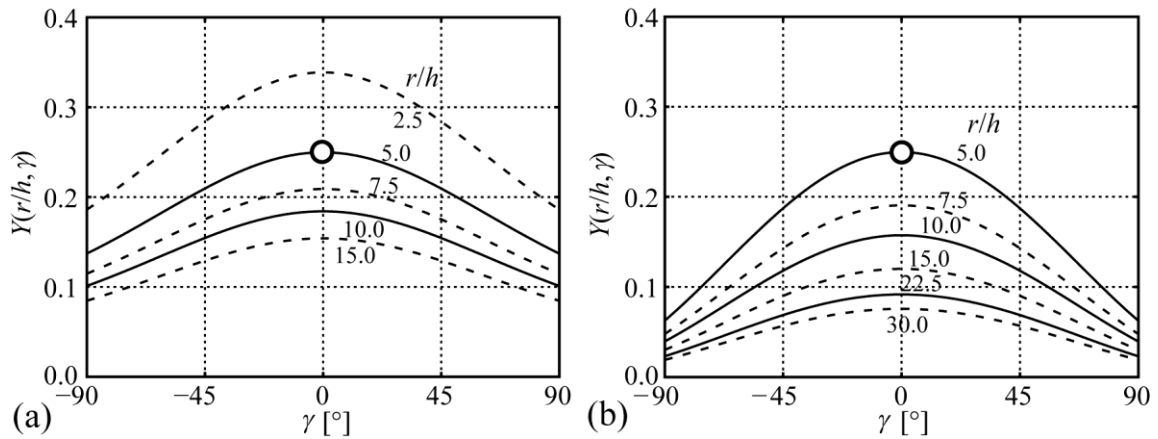


Figure 2.8 Comparison 3D relative wave height decay as a function of γ and r/h of (a) Panizzo et al. (2005b) and (b) Huber and Hager (1997) (Heller 2008).

3 Methodology

3.1 INTRODUCTION

This project aimed to study the effects of reservoir geometry on subaerial landslide generated tsunamis. This physical modelling project was based on a pre-study performed by Kinnear (2009) using the same physical model and almost the identical method.

In this chapter first scale effects involving hydraulic physical modelling and principles of Froude similitude are briefly explained. The equipment and facilities utilised in the project are introduced. This chapter presents the set up and procedures of the physical experiments and explains the measurement methods. This section ends with introducing relevant governing and dimensionless parameters which are used in this study.

3.2 SCALE EFFECTS

In general, hydraulics physical modelling involves scale effects (Heller et al., 2007). A physical model is completely similar (if not involving any scale effects) to its prototype if it satisfies the three criteria of geometric similarity, kinematic similarity and dynamic similarity (Hughes, 1993).

Geometric similarity involves similarity of ratios between all physical dimensions of the model and prototype. *Kinematic* similarity in addition to geometric similarity ratios includes the similarity of ratios of motions between particles in the model and prototype. *Dynamic* similarity includes both geometric and kinematic similarity but it also considers all ratios of vectorial forces between systems in the model and prototype is identical.

Relevant forces in hydraulics and fluid dynamics physical modelling includes inertial force, gravitational force, viscous force, surface tension and elastic compression force. Depending on which forces are more dominant in each case a different dimensionless parameter such as Froude number, Reynolds number, Weber number, or Cauchy number may be applicable. Both model and prototype should be identical in the dimensionless parameters.

Froude number ($F = V_s/(gh)^{1/2}$) is applicable for free surface, gravity fluids. Reynolds number is applicable in cases with dominant viscous forces. Weber number is a dimensionless parameter which involves surface tension and Cauchy number is relevant in situations with compressible fluids.

For pure water, compressibility and surface tension can be considered as negligible (Hughes, 1993; Heller, 2008a), hence the Froude number is the most suitable dimensionless parameter in projects involving open surface fluids.

Scale effects are applicable in models with water depths of less than 0.20 m and wave channels narrower than 0.50 m (Heller et al., 2007). Since the still water depth in this project is a constant value of 0.10 m, scale effects are considerable in this study.

3.3 MODEL SIMILITUDE

An important consideration in scale model design is the identification of the influent force ratio and the justification for the exclusion of other forces. No fluid may satisfy all force ratio requirements if the model is different in size from the prototype (Hudson et al., 1979; Hughes, 1993; Heller et al., 2007).

Froude similitude considers only inertial and gravitational forces and is often applied in fluid dynamics. According to Le Meheuté (1976) the Froude similitude applies to free surface flows with negligible viscous forces (e.g. prior to wave breaking or to short, highly turbulent flows such as in the wave breaking zone). All impulse wave models explained in Chapter 2 were modelled according to Froude similitude.

Although it is assumed that viscous forces are negligible in this study, in reality impulse waves are not completely inviscid. Also surface tension exists in the case of impulse waves. Each of these forces has a dominant effect on wave properties in both wave generation and wave propagation zones (e.g. wave amplitude decreases with increasing fluid viscosity (Section 2.3) and surface tension may influence the impact crater formation during the slide impact and wave celerity) (Le Mehauté, 1976; Heller et al., 2007).

In the process of wave generation, air entrainment and detrainment have significant effects on wave parameters. Since the bubbles sizes in hydraulic models are too large compared with the prototype, they are not scalable (Heller, 2008).

3.4 EXPERIMENTAL SET UP

3.4.1 WAVE BASIN

A wave basin, 2.00 m wide, 2.10 m long and 0.40 m deep, has been used for conducting physical model experiments for this project. A 45° ramp raised 0.40 m above the basin

bottom is used to accelerate the slide's motion. A smaller 45° ramp is located at the opposite end of the basin to the slide impact zone at 0.20 m above the bottom of the basin. The side walls of the basin are vertical. The wave tank bottom is horizontally elevated and it contains no bathymetric features.

The wave basin has been manufactured by Alda Plastics (Chandlers Ford, Hampshire) and is constructed out of 15 mm thick plexiglass (supplied by Amari Plastics, Fareham, Hampshire). The layout of the basin and its dimensions are shown in Figure 3.1.

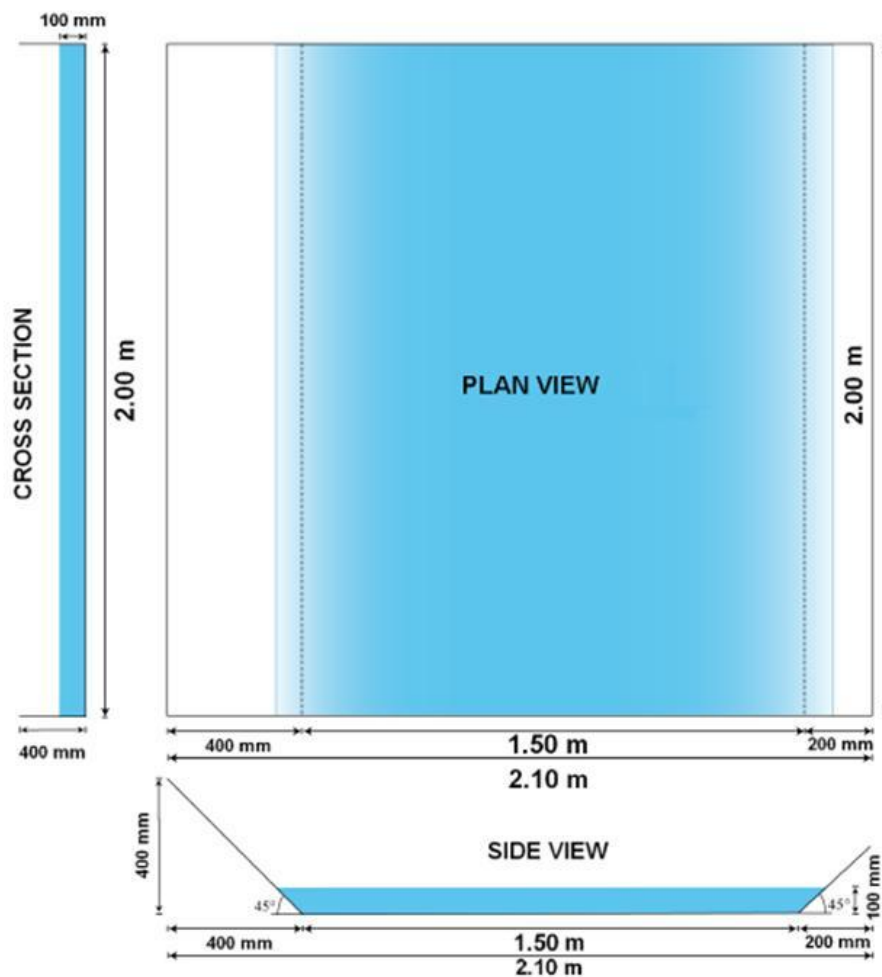


Figure 3.1 Wave basin dimensions (Kinnear, 2009).

3.4.2 LATERAL WALLS

In order to achieve diverging reservoir geometries, vertical sidewalls were diagonally located inside the basin. These vertical walls were built out of transparent acrylic plexiglass sheets. The sidewalls were manufactured in the laboratory by cutting $2050 \times 214 \times 12$ mm panels into the desired dimensions. They were placed inside the basin and stabilized using a

type of black mastic sealer. For the wave channel case the created wall was 2.10 m in length and 0.40 m deep and 0.25 m (± 5 mm) in width. This sidewall was already built and used within the study by Kinnear (2009). The lateral walls for diverging reservoir geometries were manufactured for this project specifically.

The quality of the attachment between the installed sidewalls and the 45° ramp (the slide slope) has a significant effect on the results. If the lateral wall does not extend up the slide release slope, the generation of waves will be affected and this may compromise the outputs of the experiment (Kinnear, 2009; Heller, personal communication). To avoid this error two triangular shaped walls were placed on the slope just above the still water level to fully connect the side wall to the basin and also to provide a more confined path for movement of the block.

Layouts of different reservoir geometries ($\theta = 15^\circ, 30^\circ, 45^\circ, 60^\circ$, and 75°) are shown in Figure 1.2.

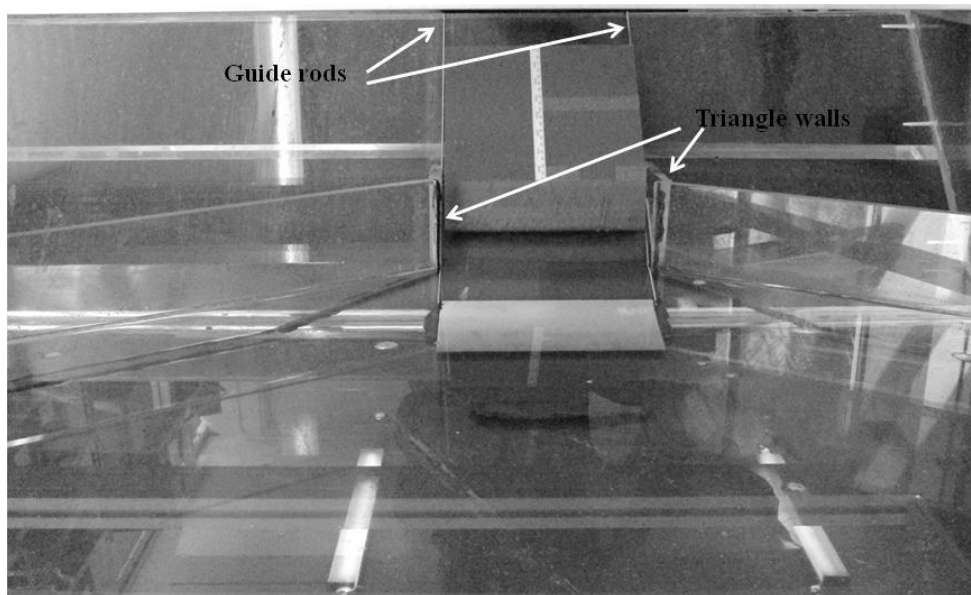


Figure 3.2 Display of 60° diverging geometry with the block, transition, stopper, triangle walls and the side bars.

3.4.3 SLIDE MATERIAL

The properties of the slide model are influential on the characteristics of the generated waves. Throughout the literature various physical modelling studies were conducted using granular or block materials. However limited tests have been conducted with the aim to compare granular slides and solid bodies (Section 2.3).



Figure 3.3 15° sidewalls and the transitions placed at two of slide release positions.

To perform experiments for this study a block model has been used to simulate the subaerial landslide. The block is of a solid material of High Density Polyethylene (HDPE; Amari Plastics) with a mass of 4.039 Kg (Kinnear, 2009). The block dimensions are 0.24 m in length, 0.25 m in width and 0.05 m in height. The bottom front edge of the block is tapered at an angle of 45° to reduce the friction between the block and surface of the slope. This also assists the movement of the block from the basin slope towards the basin bottom.



Figure 3.4 The block model.

3.4.4 *TRANSITION*

The movement of the block on the slide slope from its released point to the impact point affects the parameters of generated waves. In order to facilitate the movement of the block

into the water, a curved, aluminium sheet with a smooth surface has been fixed at the junction between the slope and the basin bottom. This item is called transition hereafter.

The transition is manufactured by Newman Precision Engineers Ltd. (Totton, Southampton, Hampshire) with dimensions of 240 mm in length and thickness of 2 mm, and is curved with a diameter of 150 mm. The thickness of the two ends of the transition has been adjusted to achieve a more flush fit to the slope and the basin bottom. Two identical transitions were applied in this project and they were located in three positions throughout the experiments. The first position (A) was located at the corner of the basin and was used for the wave channel and the 3D corner tests. The second position was in the middle of the basin (B) and the experiments corresponding to the 15°, 30° and 45° reservoir geometries were conducted from this point. The third location (C) is 0.40 m towards the centre of the basin from the left sidewall, and this point was used for experiments corresponding to the wave basin and the 60° and 75° reservoir geometries (Figure 1.4).

Figure 3.5 shows the transition between the slide and the basin bottom.

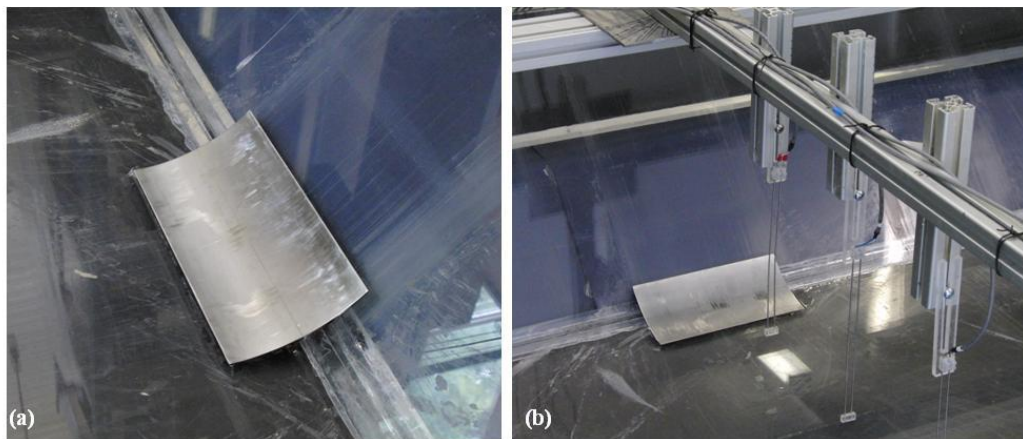


Figure 3.5 (a) the transition between the slide slope and the basin bottom (b) the transition and the wave probes.

3.4.5 MEASUREMENT EQUIPMENTS AND METHODS

3.4.5.1 RESISTANCE WAVE PROBES

Five resistance wave probes were used to measure the water surface displacement. The wave probe monitor is a simple and reliable device for measuring rapidly changing water levels in physical models. It operates by measuring the current that flows between two stainless steel wires that are immersed in water. This current is converted to an output voltage that is directly proportional to the immersed depth.

A wave probe consists of two parallel stainless steel rods with a plastic (e.g. acrylic, any type of non-conductor material) head and foot. The head is fixed to the calibration stem (Figure 3.6). The resistance probes for this project were manufactured in the laboratory and were placed along a single axis at streamwise or radial distances of 0.30 m, 0.50 m, 0.70 m, 0.90 m and 1.20 m from the slide impact point (the point where the block enters the water).

Each wave probe was connected to either a 2 or 3 channel wave monitor manufactured by Churchill Controls Ltd (Reading, United Kingdom). The final outputs of the wave probes are DC voltage.

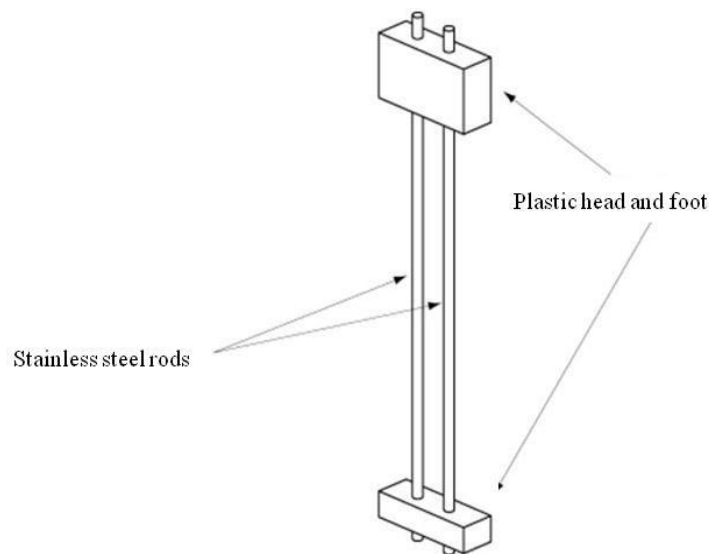


Figure 3.6 a schematic view of wave resistance probe
(altered from: <http://me-wserver.mecheng.strath.ac.uk/group2005/groupo/waveprobes2.html>)

Prior to conducting the experiments a 5 point static water level calibration of each wave probe was performed. The calibration process involved measuring the change in output voltage when the probe is raised or lowered by a known amount in still water and linearly interpolating resistance values with known immersion lengths. A Textpoint written calibration program developed by Professor John Chaplin of the University of Southampton, was applied for interpolation. By using constant values derived from the interpolation procedure, voltage data is converted into length (water surface displacement). Figure 3.7 shows an example of processed data obtained from wave probes (the voltage is already converted into water displacement) for the wave channel.

Before the calibration the water was well mixed in order to achieve a similar water quality throughout the basin. Variation in water quality leads to changes in water conductivity

therefore altering the calibration of the probes. Also the surface of the rods (probes) was cleared from air bubbles and any contaminations.

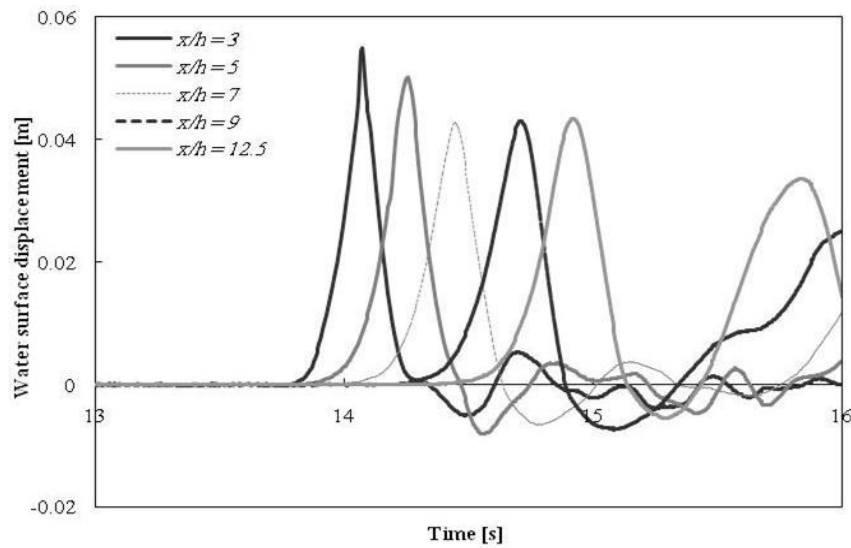


Figure 3.7 Water surface displacement from wave probe data corresponding to the wave channel.

Since the experiments were not highly repeatable each experimental set up has been conducted three times and the average value of the three runs is used for further computations. Table 3.1 and Table 3.2 show the average values for the wave height and the maximum deviation from the mean value corresponding to all geometries and for $r/h = 3$ and $r/h = 12.5$.

Table 3.1 Deviation from the mean relative wave height, for $r/h = 3$ and $\gamma = 0^\circ$.

Geometries	H/h			Mean H/h	Max. deviation (%)
	Test 1	Test 2	Test 3		
2D	0.626	0.621	0.600	0.616	2.56
15°	0.648	0.483	0.453	0.528	22.77
30°	0.458	0.468	0.420	0.528	6.44
45°	0.651	0.552	0.509	0.5705	14.07
60°	0.643	0.666	0.564	0.624	9.66
75°	0.604	0.608	0.618	0.61	1.31
3D	0.612	0.627	0.607	0.615	1.95
3D corner	0.767	0.761	0.732	0.753	2.87

Table 3.2 Deviation from the mean relative wave height, for $r/h = 12.5$ and $\gamma = 0^\circ$.

Geometries	H/h			Mean H/h	Max. deviation (%)
	Test 1	Test 2	Test 3		
2D	0.500	0.500	0.490	0.4965	1.29
15°	0.261	0.149	0.188	0.199	30.94
30°	0.116	0.108	0.081	0.102	20.26
45°	0.144	0.134	0.1205	0.1205	9.39
60°	0.1185	0.122	0.106	0.116	8.13
75°	0.112	0.115	0.115	0.116	1.64
3D	0.123	0.12	0.1195	0.121	1.60
3D corner	0.305	0.312	0.279	0.298	6.64

3.4.5.2 IMPACT VELOCITY

The block is manually released from the top of the 45° ramp and after moving down the slope hits the water surface and generates waves. In order to increase the repeatability of the tests, movement of the block on the slope should be aligned and controlled. Two metal rods are used as guides to keep the slide aligned. These rods were fixed on the slope and embedded into the basin using the same mastic seal which was applied to stabilize the side walls. Other than the guide rod the two triangular shaped items which are placed on the slope assist in aligned movement of the block (Section 3.4.2) (Figure 3.2). This method of generating waves involves errors and therefore provides another reason for the repetition of the tests. Table 3.3 shows slide impact velocity for each individual experiment and the maximum deviation from the average impact velocity, corresponding to all geometries and both slide release positions.

Two different slide release positions have been examined in this study hence two different slide impact velocities and two different slide Froude numbers are derived. For the first release position the whole volume of the block was located on the slope prior to its release. This position is referred to as the flush position and/or the first slide release position and it is identified by F_1 and V_{s1} hereafter. For the second release position the block was located with the middle of its bottom face on the slope edge. This position is referred to as the higher position and/or the second slide release position and it is identified by F_2 and V_{s2} . The values for F_1 , F_2 , V_{s1} and V_{s2} are presented in Table 3.4.

Table 3.3 slide impact velocity for each individual test and deviation from the average impact velocity corresponding to both slide release positions.

Geometries	Slide release position	Vs			Average Vs (m/s)	Max. deviation (%)
		Test 1	Test 2	Test 3		
2D	1	1.44	1.32	1.45	1.40	5.94
	2	1.68	1.81	1.97	1.82	8.24
15°	1	1.25	1.2	1.24	1.23	2.44
	2	1.72	1.56	1.53	1.60	7.28
30°	1	1.33	1.45	NA	1.39	4.32
	2	1.72	1.54	NA	1.63	5.52
45°	1	1.19	1.3	1.4	1.30	8.23
	2	1.77	1.73	1.76	1.75	1.33
60°	1	1.37	1.26	1.22	1.28	6.75
	2	1.69	1.9	1.73	1.77	7.14
75°	1	1.39	1.3	1.32	1.34	3.99
	2	1.77	1.68	1.61	1.69	4.94
3D	1	1.43	1.37	1.24	1.35	7.92
	2	1.81	1.74	1.76	1.77	2.26
3D corner	1	1.46	1.25	1.34	1.35	8.15
	2	1.74	1.88	1.96	1.86	6.45

The reason for studying two release positions was originally to compare two different wave profiles correlated to an identical geometry and also to examine behaviour of the wave corresponding to larger and smaller impact velocities. However it was observed that the difference in slide release positions does not make a considerable difference in slide impact velocity in this case.

In this project an EX- F1 Casio digital camera was utilized to capture the block impact moment. By choosing the 60fps option, the camera takes 60 continuous frames per second (in reality 59.94 frames per seconds are shot (Thomas Chambers Casio Customer Support, personal communication)). The Microsoft Office Manager software was then used to analyse the two frames prior to the impact moment to manually measure the slide impact velocity (Figure 3.9).



Figure 3.8 Wave channel: the camera and the resistance wave probes

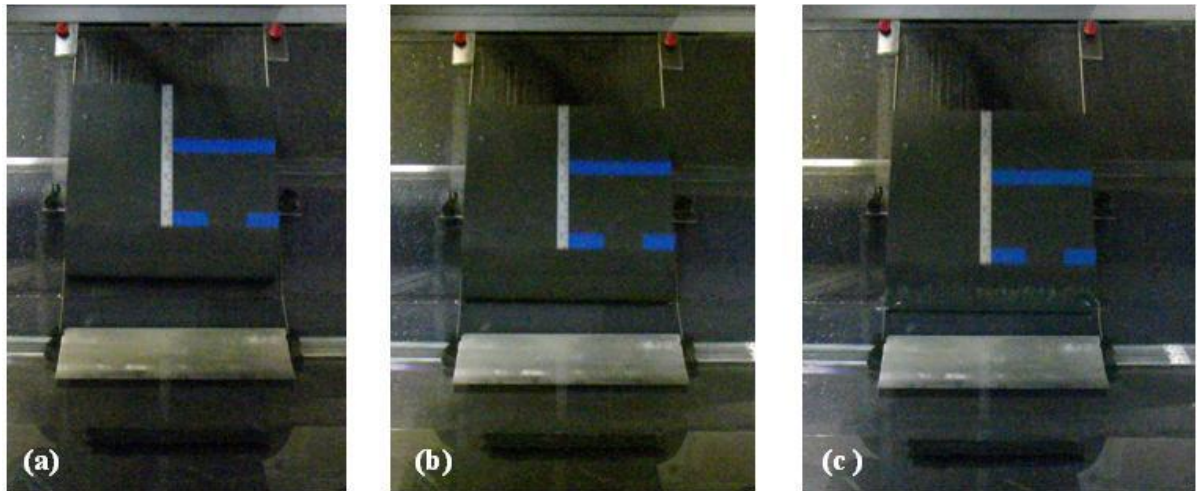


Figure 3.9 wave basin: the impact moment. (a) and (b) are used for calculating the slide impact velocity.

3.4.6 EXPERIMENTAL SET-UP

Most of the previous studies on impulse waves have investigated maximum wave height H_M and maximum wave amplitude a_M . But in cases where the opposite shoreline or the structure is located at a distance from the slide impact point, the computation of wave properties is required from formulas for the wave decay in terms of distance from slide impact zone (Heller, 2008b). Also, in order to calculate wave run-up and overtopping on the structures other than wave height H and wave amplitude a , values for wave period T are

required (Müller, 1995, Heller et al., 2005). Therefore decay of wave amplitude and wave height in terms of relative distance and wave period for different reservoir geometries have been investigated in this project.

The above parameters can be obtained from analysing wave probe data at five different relative streamwise (in the 2D case) or relative radial distances. The measurement components were recorded in the channel axis in the 2D case ($\theta = 0^\circ$) and along certain wave propagation angles ($\gamma = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$) corresponding to different reservoir geometries.

The experimental procedure was as follows. The water depth was checked and adjusted if required prior to the experiments. The wave probes were statically calibrated. Time was allowed for the natural oscillations of the water surface in the basin (or the channel) to completely stop before the experiment began. The landslide block model was released and tsunami was generated. Atypical experiment lasted from 6 minutes to 30 minutes, depending on whether impact velocity photos were taken.

The block may continue its motion on the basin bottom prior to coming to rest. However it did not travel the same distance for all cases. In order to ensure the block stopped in the same position a stopper was built and placed on the basin bottom. The stopper was comprised of the mastic sealer which was used to stabilize the sidewalls. The dimensions of the stopper were small compared to the wave height therefore it did not affect the wave parameters (Chen, 2009).

3.5 EXPERIMENTAL GOVERNING AND DIMENSIONLESS VALUES

Table 3.3 presents the values of governing and dimensionless parameters in this project.

Different geometries are identified by the parameter reservoir side angle θ . For each of the geometries water surface variations were measured for different wave propagation angles. Depending on the value of θ , not all of the wave propagation angles were applicable (e.g. for the 15° geometry the wave parameters are only measured for $\gamma = 0^\circ$).

The only parameters which were systematically varied in this project are V_s (and therefore Froude number), γ , and θ .

Table 3.4 Experimental values

Parameter	Symbol	Unit	Value
Still water depth	h	m	0.10 (± 0.001)
Slide width	b	m	0.24
Slide thickness	s	m	0.05
Bulk slide density	ρ_s	Kg/m ³	1537.40
Bulk slide porosity	n	-	0
Bulk slide volume	V_s	m ³	0.002634
Slide impact angle	α	degree	45
Slide impact velocity	V_s	m/s	1.33 (± 0.04); 1.75 (± 0.07)
Slide Froude number	F	-	1.34 (± 0.04); 1.74 (± 0.07)
Relative streamwise distance	$X = x/h$	-	3; 5; 7; 9; 12.5
Relative radial distance	r/h	-	3; 5; 7; 9; 12.5
Wave propagation angle	γ	degree	0; 15; 30; 45; 60; 75; 90
Reservoir side angle	θ	degree	0; 15; 30; 45; 60; 75; 90

3.6 SUMMARY

To investigate the effects of geometry on landslide induced tsunamis a set of experiments were performed in a wave basin. A block model was released from a 45° ramp into the water to simulate the subaerial landslide. This chapter presented an overview on scale effects in hydraulics physical modelling. The components of the physical model were introduced and information about the function of the applied tools and equipment was presented. Also the process of conducting the experiments was explained in detail. Finally, the relevant governing and dimensionless parameters were introduced.

4 Experimental Results

4.1 INTRODUCTION

A total of 168 experiments were conducted in order to study behaviour of impulse waves in general geometries. These experiments were ranging over a wave channel (2D), a wave basin (3D), two different slide release positions and three different slide impact points Figure (1.4).

Information contained in chapter 2 *Literature Review* relating to wave energy dissipation indicates that wave height decreases with relative distance from the impact point. It is also expected to observe smaller waves in geometries with larger side angle θ . However, this is not consistently the case in this project.

The following chapter presents the obtained results. In this section the measured values for relative wave height H/h , relative wave amplitude a/h , relative wave period T_r and the decay of these parameters with relative distance in different reservoir geometries are presented and further compared with each other.

Since each experiment has been repeated three times, the presented values are the average of three runs of the same experimental set up (Section 3.2).

In this chapter the terms first/flush slide release position, first/lower impact velocity and first Froude number are referred to Froude number $F_1 = 1.34$ and impact velocity $V_{s1} = 1.33$ (m/s). Also the phrases second/higher slide release position, second/higher impact velocity and first Froude number are referred to Froude number $F_2 = 1.74$ and impact velocity $V_{s2} = 1.73$ (m/s) (Chapter 3).

4.2 WAVE CHANNEL

Figure 4.1 shows relative wave height decay in the wave channel (2D) corresponding to two slide impact velocities. The black line identifies relative wave height for the first slide release position (F_1) and the gray line higher slid release position (F_2) (Section 3.4.5.2).

The results for F_1 show a maximum relative wave height of 0.62 at $X = 3$ this value has decrease by 19.5% H/h of 0.49 at $X = 12.5$.

For the F_2 case a relative wave height of 0.72 at $X = 3$ has decreased to 0.52 m at $X = 12.5$ corresponding to a reduction rate of 28.1%.

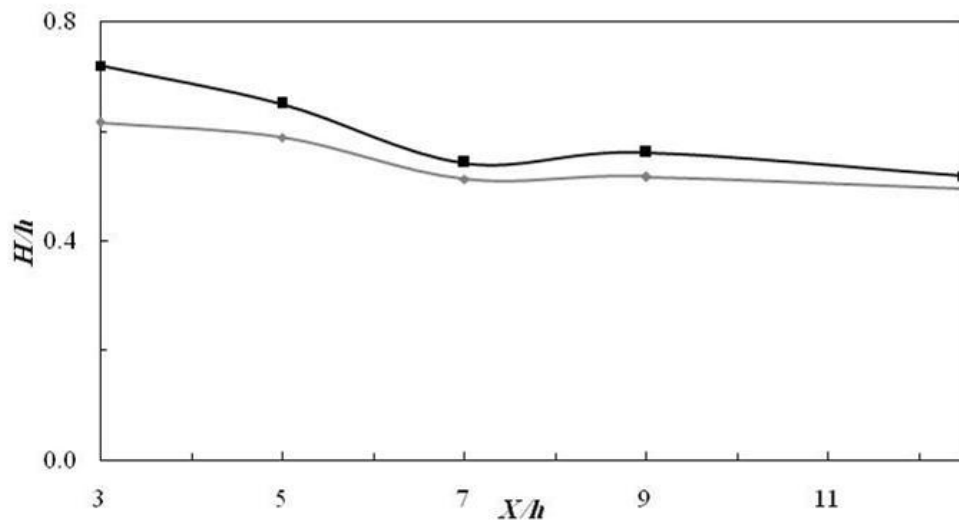


Figure 4.1 Wave channel: Relative wave height H/h as a function of relative streamwise distance $X=x/h$ for the two slide Froude numbers.

It can also be observed from Figure 4.1 that the wave profile decreases from $X = 3$ to $X = 7$, however the wave height increase from $X = 7$ to $X = 9$. This may be due to the splash affecting the first two wave probes and the wave profile is not a yet well defined (personal communication, Heller, Heller & Hager, 2010). Frequency dispersion may also explain this behaviour. In intermediate and deep water waves are dispersive. Wave components separate since their celerity depends on wave period (Linear wave theory, Section 2.2) (Dean and Dalrymple, 1991).

$$c = L/T, \quad T = \left(\frac{gT}{2\pi} \right) \tanh\left(\frac{2\pi}{L}\right)$$

where

c $[LT^{-1}]$ = wave celerity

T $[T]$ = wave period

L $[L]$ = wave length

g $[LT^{-2}]$ = gravitational acceleration

4.3 WAVE BASIN (3D)

4.3.1 RELATIVE WAVE HEIGHT DECAY

Figure 4.2 shows relative wave height decay in the wave basin for $\gamma = 0^\circ$. The solid black line indicates relative wave height decay for the higher slide release position and the dashed gray line shows wave height decay for the flush release position.

Figure 4.2 shows the relative wave height of 0.62 at $r/h = 3$ and 0.12 at $r/h = 12.5$ for the flush release position. In the higher release position the highest wave height of 0.76 m was measured at $X = 3$ and the lowest wave height of 0.13 m at $X = 12.5$. The measurements denote a reduction of 80.3% and 83.1% respectively.

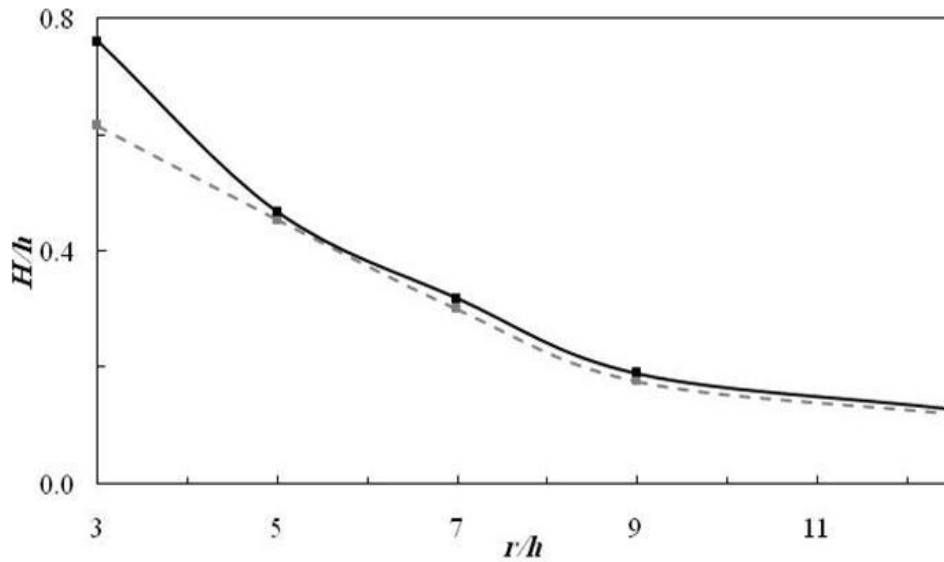


Figure 4.2 Wave basin: wave propagation angle $\gamma = 0^\circ$: Relative wave height as a function of relative stream wise distance r/h .

Overall faster relative wave height decay was observed between $3 \leq r/h \leq 7$ and the decay becomes less for $r/h > 7$. This was observed for both Froude numbers in both wave channel (2D) and wave basin (3D) geometries.

Both Figure 4.1 and 4.2 indicate that wave heights do not significantly differ with changing the slide release position. In general results from the F_2 case are found to be factor of 1.0-1.2 larger compare to that of the F_1 case (obtained from all wave propagation angles and all geometries).

Since wave profiles from the two different slide impact velocities were not significantly different, results from the higher impact velocity are not under taken for further studies on

different geometries. Hence hereafter only results from the flush release position with Froude number F_1 are discussed.

4.3.2 WAVE PROPAGATION ANGLES

Figure 4.3 shows results for relative wave height H/h as a function of wave propagation angle γ corresponding to the wave basin case.

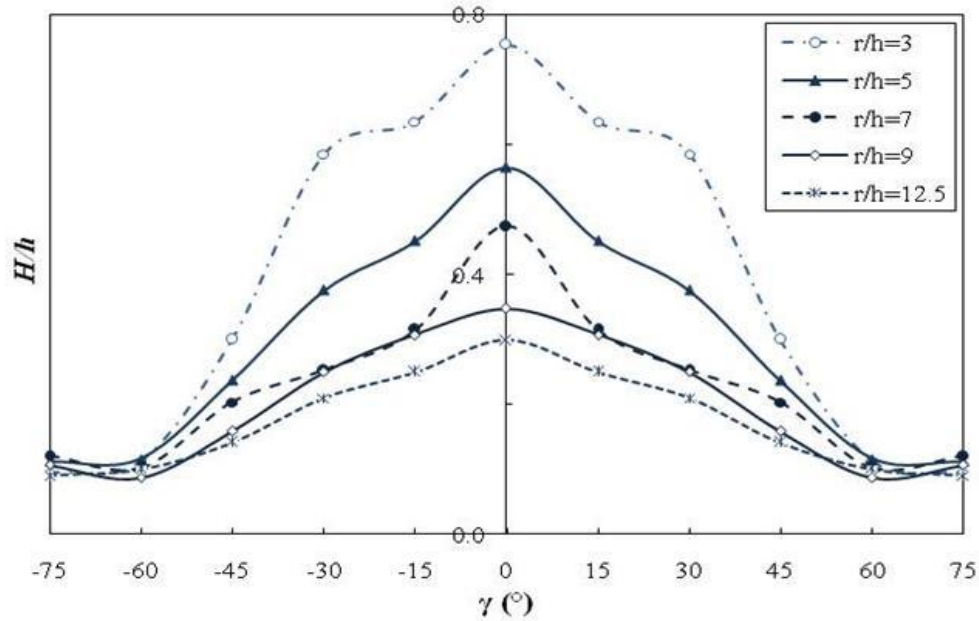


Figure 4.3 Wave basin: relative wave height H/h versus wave propagation angle γ , corresponding to 5 relative distances.

Figure 4.3 shows that H/h decreases with relative distance from slide impact point.

This Figure also indicates that the maximum of wave height is observed on the slide propagation axis at $\gamma = 0^\circ$. This has been confirmed in previous studies on impulse waves by Slingerland & Voight (1979), Huber & Hager (1997), and Panizzo et al. (2005b) amongst others.

As the wave propagates its wave height decreases due to radial and transverse dissipation. As a result it is expected to observe smaller wave heights at larger wave propagation angles (Chapter 2 and Chapter 5).

Two of the resistance wave probes have recorded larger wave height for $\gamma = \pm 75^\circ$ compared to $\pm 60^\circ$, which is in contrast with the general expectation since the probes are located in vicinity of sidewalls in the $\pm 75^\circ$ case, this can be explained by occurrence of edge

waves. Edge waves are trapped topographic waves which travel alongshore, studying this phenomenon can be of special interest (Polukhina et al., 2006, Di Risio et al., 2009)

Figure 4.3 also denotes a sudden drop in wave height from $\gamma = 0^\circ$ to $\gamma = \pm 15^\circ$, whereas for angles larger than $\pm 15^\circ$ the wave height follows a smoother curve (this can be seen for all relative distances).

4.4 GENERAL GEOMETRIES

Figure 4.4 displays relative wave height versus wave propagation angle for different relative distances r/h reservoir side angle θ geometries.

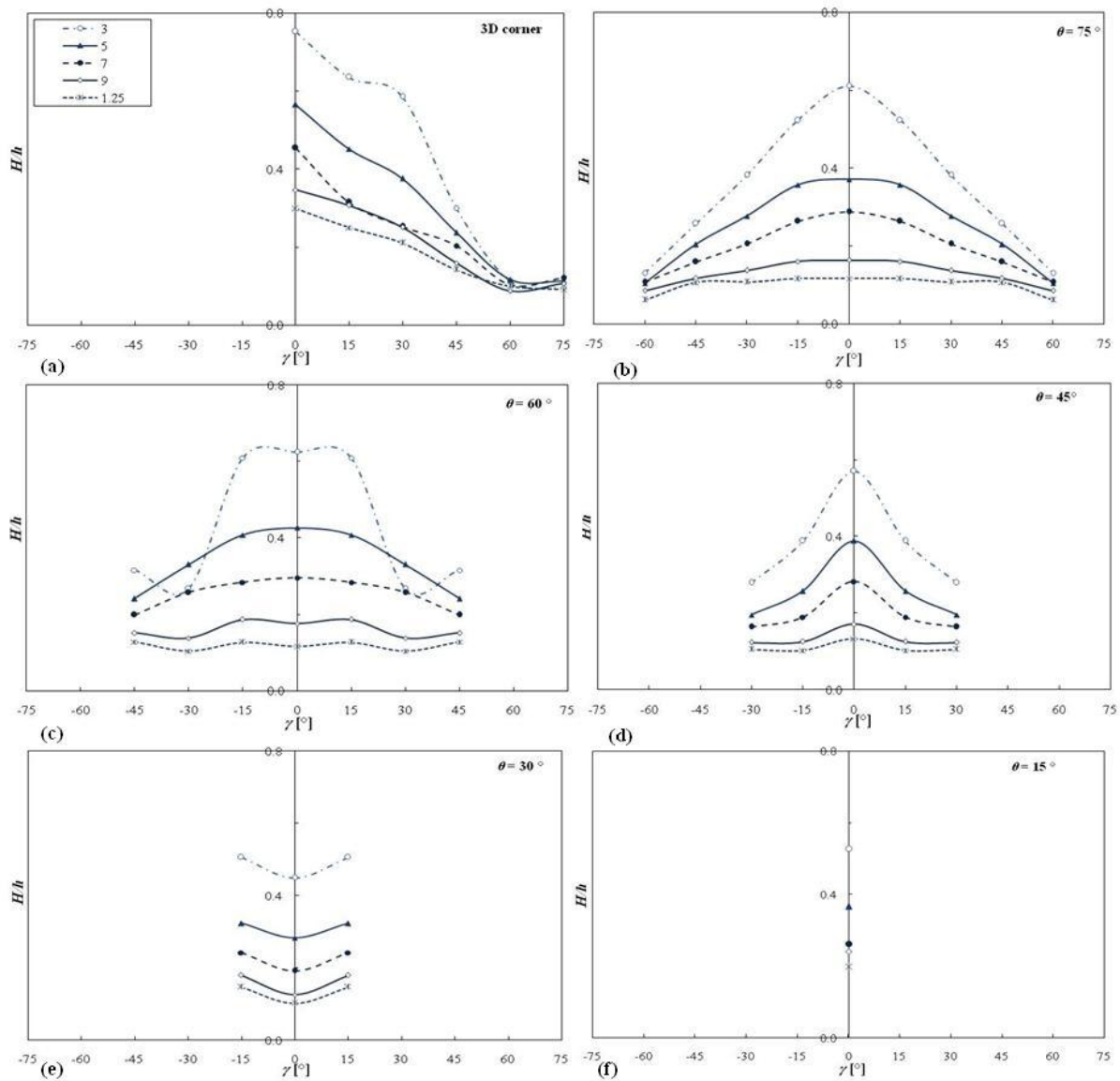


Figure 4.4 All reservoir side angles: relative wave height H/h versus wave propagation angle γ ; legend: see panel (a).

It is observed that in general as the wave propagation angle γ increases the relative wave height H/h decreases (due to radial and transverse wave spread). Figure also denotes that maximum of relative wave height corresponding to all geometries and all relative radial distances is to be found in approximately slide impact direction at γ between -15° and $+15^\circ$.

The presence of edge waves can be seen in some of the reservoir geometries.

4.5 COMPARISON BETWEEN GEOMETRIES

Since scale effects may be consistent for all conducted tests in this project, different wave parameters corresponding to different geometries can be compared together. This will be done in order to study effects of geometry on impulse wave parameters.

4.5.1 WAVE HEIGHT

Figure 4.5 shows the relative wave height decay in all investigated geometries for $\gamma = 0^\circ$.

Figure 4.5 illustrates that the relative wave height in the wave generation zone corresponding to the 2D and 3D geometries is almost equal. This has been previously approved by Huber (1980) and will be discussed more in chapter 5 *Discussion and Analysis of Results*.

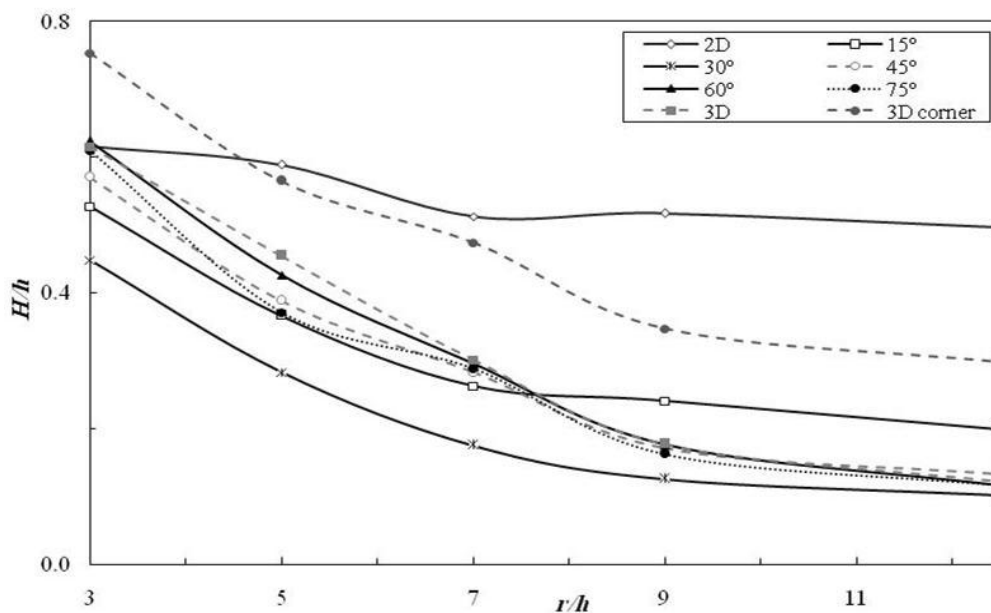


Figure 4.5 Relative wave height decay for all tested reservoir geometries and $\gamma = 0^\circ$.

Figure 4.5 shows that H/h between $r/h = 3$ to $r/h = 12.5$ for $\theta = 15^\circ, 30^\circ, 45^\circ, 60^\circ$, and 75° decays as 62.2%, 77.3%, 76.7%, 81.4%, and 81.0%. These results generally agree with the fact that the wave height decay increases with increasing θ . For the 3D corner case the relative wave height of 0.75 at $r/h = 3$ decreases to 0.30 at $r/h = 12.5$ indicating a reduction by 60.4%. This value lies between reduction rate in the 2D (19.5%) and 3D (80.3%) cases.

Figure 4.5 also shows that the 3D corner geometry has the highest wave height in wave generation zone. The reason for this phenomenon is not fully understood but it may be caused by wave reflection from the side wall. In the wave propagation zone (for other four probes), however the value for H/h is smaller than the corresponding parameter in the wave channel.

The 30° diverging geometry records the smallest wave heights for all relative distances. Hence it can be observed from Figure 4.5 that relative wave heights in different reservoir geometries are not following a logical order. The possible reasons for these observations are discussed further in this and the following chapter.

Figure 4.6 shows relative wave height H/h as a function of wave propagation angle γ for different reservoir geometries at $r/h = 3$ and $r/h = 5$, respectively.

Figure 4.6 can be used for comparison of relative wave height as a function of wave propagation angle in all tested geometries. These two plots approve the obtained results from Figures 4.4 and 4.5.

Presence of edge waves can be seen in some of the geometries such as 30° and wave basin. Although it can be said that edge waves in diverging reservoir geometries are different from those in wave basin (3D) since in the later case the walls are 45° inclined whereas in cases where $\theta = 30^\circ$ or 60° sidewalls are vertical and this may affect the properties of these waves. Further studies need to be done in this area (Kinnear, 2009).

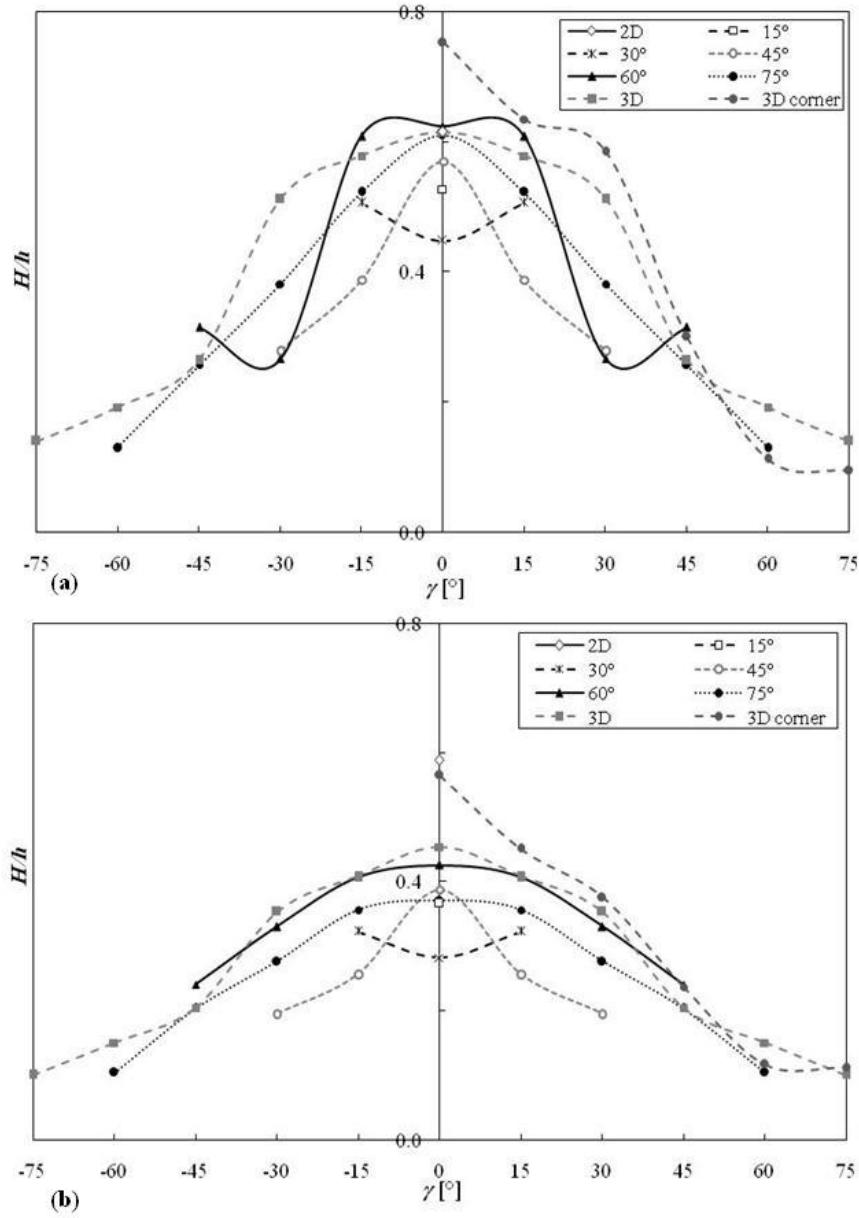


Figure 4.6 Relative wave height decay as a function of wave propagation angle γ . (a) $r/h = 3$ and (b) $r/h = 5$.

4.6 WAVE AMPLITUDE

Figure 4.8 shows the experimental results for the relative wave amplitude a/h decay corresponding to all investigated geometries.

The relative wave amplitude a/h , at $r/h = 3$, is 0.59 in the wave channel and 0.40 in the wave basin case.

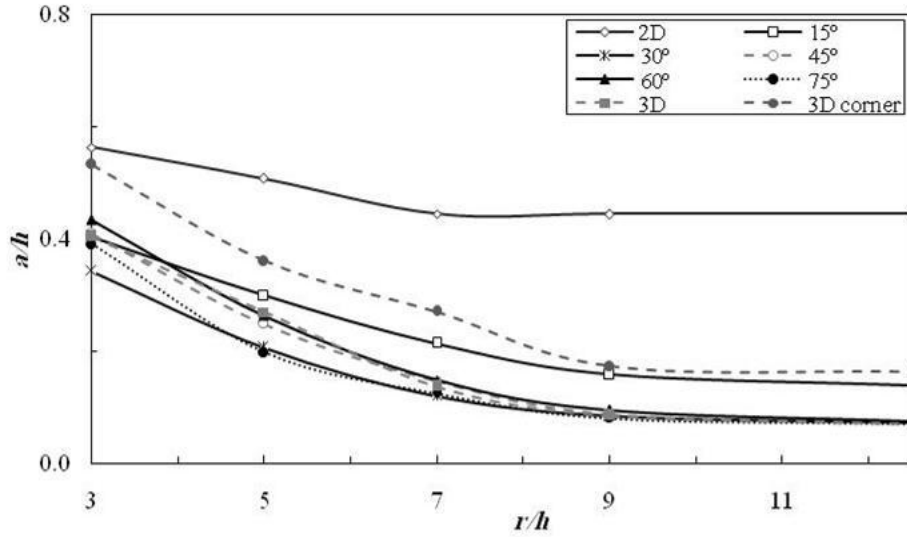


Figure 4.7 Relative wave amplitude decay correlated to all geometries and $\gamma = 0^\circ$.

Figure 4.7 denotes that for all geometries, waves generated in the wave channel (2D) have the highest amplitude both in generation and propagation zones. By comparing Figure 4.7 with Figure 4.5 it can be seen that relative amplitude decay does not follow the same order as relative wave height decay.

In order to study behaviour of wave troughs in different geometries Figure 4.8 is plotted.

Figure 4.8 shows that troughs get smaller in geometries with larger side angle θ . It can be seen that a/H , at $r/h = 3$, for the wave channel ($\theta = 0^\circ$) is equal to 91% and 65% for the wave basin ($\theta = 90^\circ$).

In general the results of this study are not similar to those of Heller and Hager (2008) who found that in average wave height is approximately 5/4 (80%) of wave amplitude. In the present study this ratio differs from 88% (for $\theta = 0^\circ$) to 54% (for $\theta = 75^\circ$) (This ratio is the average value for the five investigated relative distances).

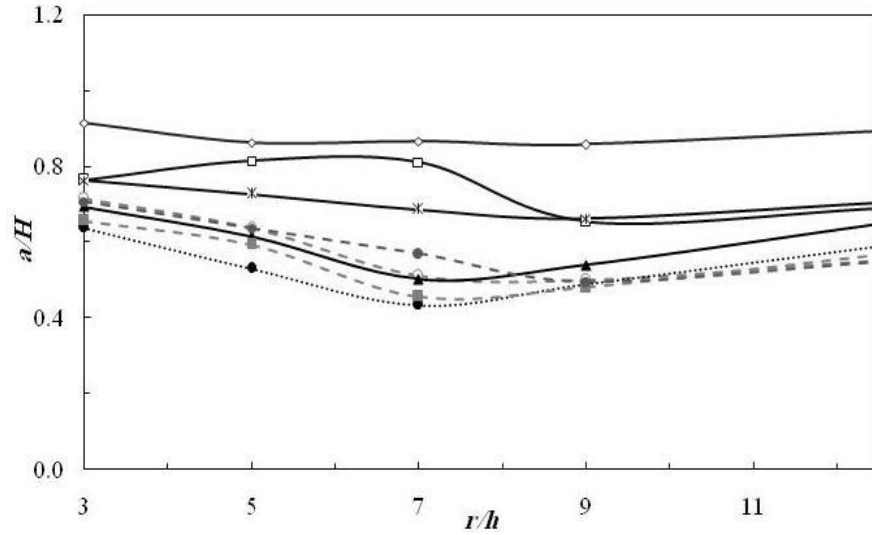


Figure 4.8 All geometries: amplitude over wave height ratio decay for $\gamma = 0^\circ$; Legend: see Figure 4.7.

Figure 4.9 shows relative wave amplitude as a function of wave propagation angle for all reservoir side angles $\theta = 0^\circ$ (2D) to $\theta = 90^\circ$ (3D).

By comparing Figure 4.9 and Figure 4.6 it can be seen that in general relative amplitude a/h and relative wave height H/h follow a similar trend.

It can be seen from Figure 4.9 (b) that the difference between amplitudes corresponding to different geometries ($\theta = 15^\circ$ to $\theta = 75^\circ$) and the 3D case is less than 7%.

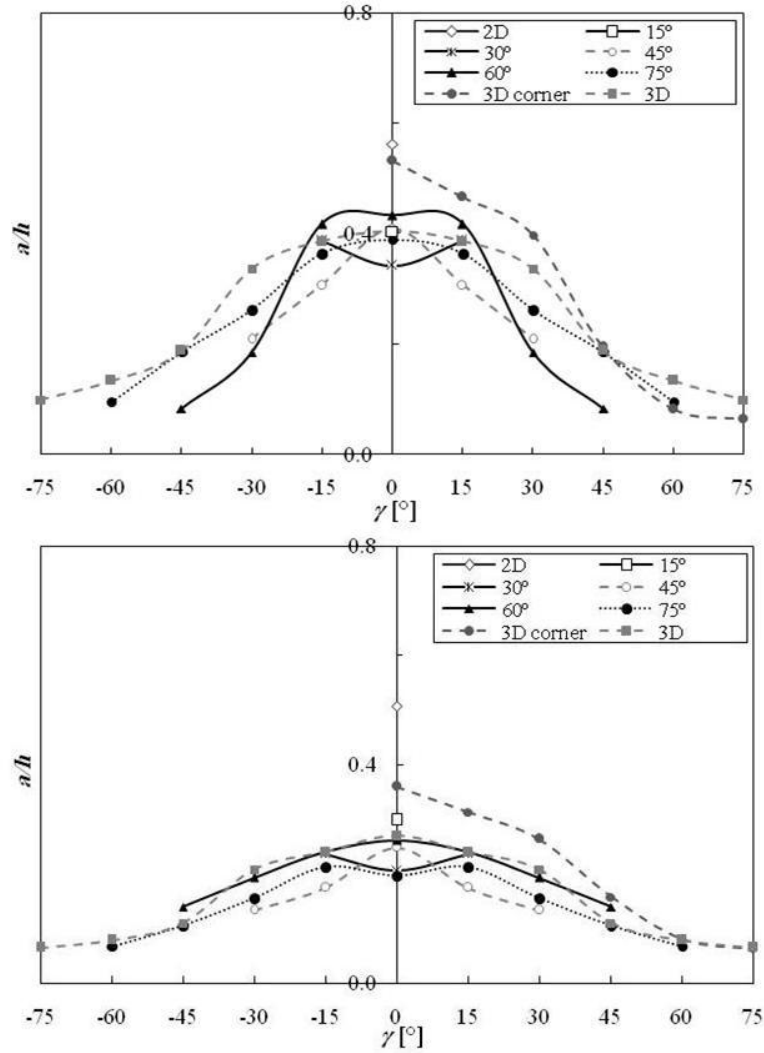


Figure 4.9 All geometries: Relative wave amplitude as a function of wave propagation angle. (a) results at $r/h=3$ and (b) results at $r/h=5$.

4.7 WAVE PERIOD

In order to make the wave period comparable and dimensionless the parameter relative wave period $T = (g/h)^{1/2}$ is used.

Figure 4.10 shows the relative wave period decay for all geometries. The correlation for wave period T is often worse than wave height and wave amplitude. However to calculate the effects of impulse wave on the structures wave period is less important than other parameters (Heller et al., 2009).

It can be seen from Figure 4.10 that in general relative wave period increases with relative distance.

In Figure 4.11 relative wave period is shown as a function of wave propagation angle. It can be seen that especially in Figure 4.11(a) the relative wave period correlated to different geometries does not follow a regular trend.

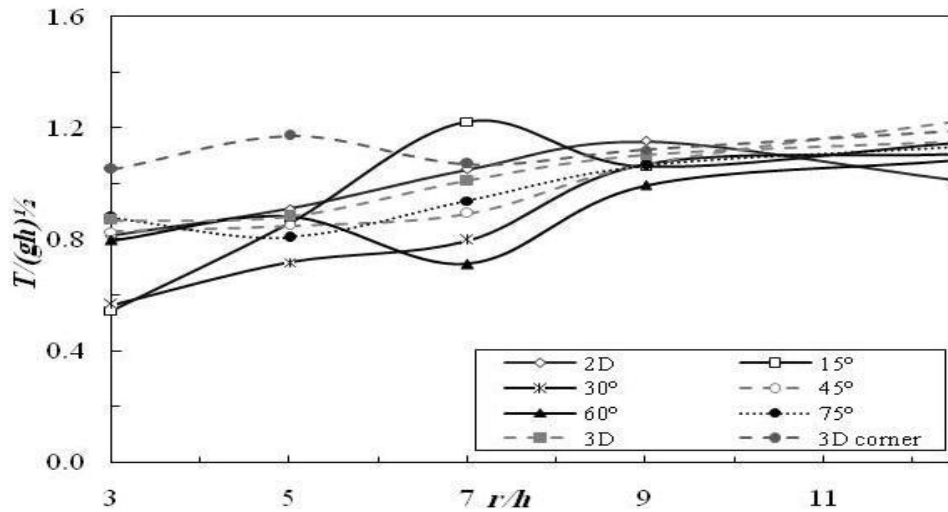


Figure 4.10 All geometries: relative wave period as a function of relative distance.

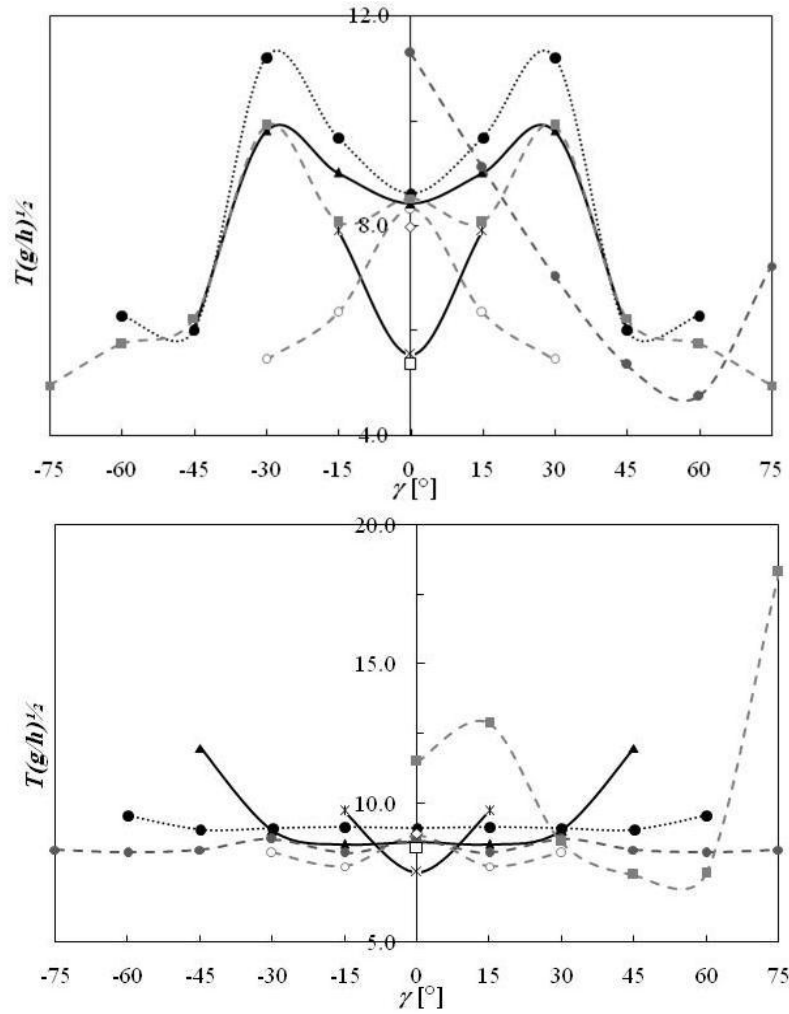


Figure 4.11 Relative wave height as a function of wave propagation angle γ . (a): results at $r/h=3$ (b) results at $r/h=5$; legend: See Fig. 4.6

4.8 SUMMARY

In general by studying the previous technical literature on impulse waves' parameters it was expected to observe a decreasing trend in wave height H with increasing the reservoir side angle θ .

Results of this project are summarised as below:

4.8.1 WAVE HEIGHT

- The 3D corner tests result in the highest wave height in the impact (wave generation) zone.
- Waves generated in the wave channel have the highest wave height in the wave propagation zone relative to all other investigated geometries.

- The lowest wave height in both wave generation and propagation zones is correlated to the 30° diverging reservoir geometry ($\theta = 30^\circ$).
- The major exception to results of this project is corresponding to $\theta = 15^\circ$, 30° and 45° . This may be attributes to installation of the transition in the wave basin. The transition was moved and relocated in the middle of the basin for these sets of experiences ($\theta = 15^\circ$, 30° and 45°) if the item was not flush or well sealed then the generated impulse wave can be affected and the quality of wave data compromised. Also roughness of the transition may have increased since it had been immersed for a while prior to experiments. (Section 3.4.4 and 3.4.5).
- For all geometries the maximum of relative wave height is to be found in approximately slide impact direction at γ between -15° and 15° .

4.8.2 WAVE AMPLITUDE

- In this project the wave amplitude generally follows the same trend as the wave height however it is more regular.
- Results of the present study show that wave troughs change with the geometries.
- The wave troughs decrease with increasing reservoir side angle θ .

4.8.3 WAVE PERIOD

- In general wave period is more irregular than wave height and the wave amplitude.
- Overall relative wave period increase with relative distance from the impact zone.
- Further from the wave generation zone (at $r/h = 5$) irregularity decreases.

5 DISCUSSION AND ANALYSIS OF RESULTS

5.1 INTRODUCTION

In case of gravity water waves, wave height damping occurs. As the wave propagates its height (and amplitude) decreases due to transverse and radial energy spreading. In comparison between a wave channel 2D and a wave basin 3D theory predicts that as in 3D wave travels over a larger area the wave height decreases more rapidly than in 2D (Slingerland & Voight, 1979; Huber & Hager, 1997; Panizzo et al., 2005b; Walder et al., 2003). In this project as the reservoir side angle θ increases the area in which wave propagates also increases. As a consequence the general expectation is to observe wave heights (and wave amplitudes) decrease as the reservoir side angle increases from 2D, 15°, 30°, 45°, 60°, 75° to 3D (the 3D corner case is excluded from this prediction because of presence of reflective waves which may dominantly affect wave characteristics). The results of this project, however, do not always follow the predicted trend (Chapter 4).

In this chapter, in order to explain effects of different geometries on impulse wave characteristics and also to justify the discrepancies between the observed and predicted trends, wave parameters corresponding to different geometries are compared. Relative wave height $H(x, r)/h$, relative wave amplitude $a(x, r)/h$ and the decay of these parameters are compared to the corresponding parameters from Kinnear (2009). The similarities and differences between them are then discussed. To achieve the objectives of this project (Section 1.2) the values of relative wave height and relative wave height decay from general geometries are compared to these values derived by using Eq. (5.3). This section continues with comparing the measured H/h values correlated to $\theta = 15^\circ$ and 30° with the results obtained from Green's Law. This chapter ends with comparing H/h as a function of γ for the 3D and 3D corner test with the corresponding parameters from studies of Panizzo et al. (2005) and Huber and Hager (1997).

5.2 WAVE HEIGHT

5.2.1 COMPARISON BETWEEN GEOMETRIES

Figure 5.1 shows relative wave height H/h decay as a function of wave propagation angle γ for all geometries at $r/h = 3$ and 5.

It can be observed that relative wave heights in Figure 5.1(b) follow a more regular and logical trend than in Figure 5.2(a). This may be the case since $r/h = 3$ is located in wave generation zone. In the wave generation zone several complicated phenomena such as air entrainment and air detrainment, existence of vortexes and turbidity cause major irregularities and compromise the results. In this zone several variables are involved. Predicting these processes or systematically studying them in the physical model for this project is not possible. Occurrence of some of these physical processes cannot be considered in scale effects (e.g. existence of air bubbles) (Sections 3.2 and 3.3). Also according to Whalin (1965) most equations are not valid near the area of wave generation because some distance is required for the displaced water to evolve into wave train (Fritz et al., 2010).

Figure 5.1 shows that relative wave height values corresponding to the geometries with $\theta = 15^\circ$, 30° , and 45° are significantly smaller than expected (the relative wave heights are expected to decrease from 2D, 15° , 30° , 45° , 60° , 75° , 3D respectively). This may be due to small slide impact velocity. While conducting the experiments it was observed that the slide was moving slower and slightly discontinues on the 45° slope (slide slope), in these cases (especially for $\theta = 15^\circ$ and 30°) compare to the other cases. Lower slide impact velocity causes a smaller slide Froude number F . Froude number is directly related to H/h in the empirical equations for calculating $H(x, r)/h$ (Tables 3.1 and 3.2).

Discontinuous and slow motion of the slide on the slide slope may increase the time of underwater landslide motion t_s (time of underwater landslide motion is related to slide kinematics after slide impact). t_s is inversely related to H/h since as t_s increases less kinematic energy is converted from the landslide to water particles and as a result smaller waves would be generated (Walder et al, 2003; Panizzo et al., 2005a). Further studies for more clarification are required.

Another reason for this discrepancy may be increased friction between the transition and the slide. The transition has been submerged before conducting this set of experiments (the 15° , 30° and 45° diverging geometries) for a period of about three weeks. A layer of lime may have increased the roughness of transition surface.

The quality of fit and how the transition is sealed between the 45° slide slope and the bottom of the wave basin can also affect the slide motion and its impact velocity.

Analysing Figure 4.6 denotes that the relative wave heights corresponding to geometries with $\theta > 45^\circ$, especially for $r/h = 5$, follow a similar trend with small deviations. This finding

may be considered in further studies for example in case of a wave basin study instead of using a rectangular basin a basin with inertial angle of less than 90° can be utilized and as a reason the volume of the basin reduces and this may reduce the costs of the project. Also a specific project may become feasible in locations with smaller areas.

5.2.2 COMPARISON WITH PREVIOUS STUDIES

5.2.2.1 COMPARISON WITH RESULTS OF KINNEAR (2009)

Figure 5.1 displays relative wave height versus wave propagation angles from Kinnear (2009) at $r/h = 5$. The results from the two geometries wave channel and the 15° diverging wall are not included (the figure is taken from the original project and no changes have been made).

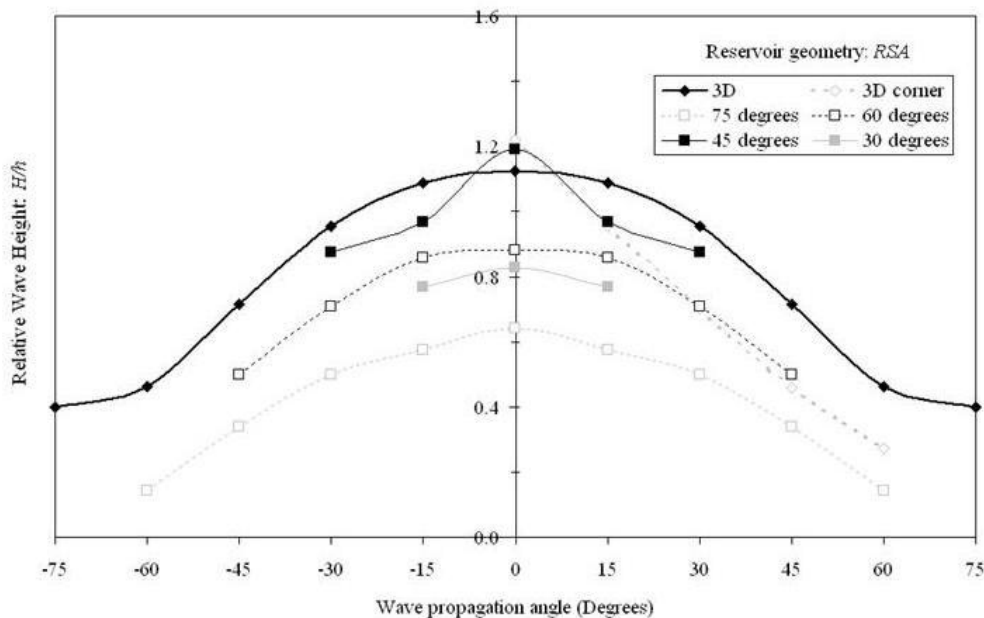


Figure 5.1 Diverging reservoir geometries from Kinnear (2009).

Comparing Figure 4.6(a) and 5.1 identifies that generally relative wave heights do not follow the same order in the two studies. However Figure 5.2 shows that H/h corresponding to different geometries do not follow the expected order either.

Analysing Figure 5.1 shows that the values of H/h for the 3D corner case are close the measured values in the wave basin at $\gamma = 0^\circ$. However, H/h in the 3D corner case decrease faster than in the wave basin. Figure 4.6(b) illustrates completely different outputs. In the present study H/h value at 0° is much closer to 2D case than to the 3D case and values in the 3D corner case are larger and decay faster compared to the 3D case.

Also Figure 5.1 does not show presence of edge waves or reflective waves for the 3D corner case and 30° diverging geometry.

Although the same physical model is utilized in both projects and also the same amount of scale effects are involved, some differences in the applied equipments and measurement methods may be the reason for the mentioned discrepancies.

Two different transitions have been applied in the two studies. Kinnear (2009) had placed a triangular section of acrylic at the junction between the slope and the basin bottom. Differences in shape and type of the transition cause differences in the behaviour of the block during the impact which leads to different impact velocities and different Froude numbers. Motion of the block from the impact moment till it stops under the water can affect the shape and magnitude of the generated waves. The shape of the transition affects the underwater motion of the block. Hence use of two different transitions can be considered as the main reason for the differences observed in Figure 4.6(b) and Figure 2.5. These can be the reason for differences in the derived values in the two studies. However the fact that H/h in the two studies follows different trend may not be completely explained by the above reasons.

Also the quality of fit and alignment of the diverging sidewalls is effective on wave parameters and should be considered. In Kinnear (2009) (for some of the geometries) the fit was not flush or if the desired geometry did not continue fully up the inclined block release slope to the slide impact zone then the generated impulse wave could be affected and the quality of the wave data compromised (Kinnear, 2009) this was improved in the present study (Section 3.4.2).

An accelerometer was used for measuring slide impact velocity in Kinnear (2009). This equipment was attached to the block which could affect the motion of the block and its impact velocity and cause difference between the two projects.

Difference in quality of the water could also be an influential parameter in causing deviations in results of the two projects. Since quality of water affects its conductivity calibration ratio of the probes differ with changes in water quality (Section 3.4.5)

Despite all the differences some similarities can be noted by comparing Figure 4.6(b) to Figure 5.2.

In both figures a significant difference in value of H/h at $\gamma = 0^\circ$ and $\gamma = 15^\circ$ corresponding to the 45° diverging geometry can be observed.

In both projects results correlated to 3D, 75° and 60° geometries follow a similar trend although the deviation between the values in Figure 5.2 is bigger as compared to the deviations in Figure 5.1(b). In general yet the behaviour of impulse waves in general geometries is not fully understood and a definite conclusion cannot be made. Further studies are required in this field.

5.2.2.2 COMPARISON WITH EMPIRICAL EQUATIONS OF HUBER AND HAGER (1997) (EQ. (2.13) AND EQ. (2.19))

In order to compare the results of this study with the existing formulas and also to derive a formula including a term which expresses geometry variation, the results are compared with Eq. (2.13) and Eq. (2.19).

According to equations (2.13) and (2.19), $H(x \text{ or } r)/h$ is related to $(x \text{ or } r)/h$ with a power law:

$$H/h \propto (r/h)^n \quad (5.1)$$

Table 5.1 contained the calculated exponents for each geometry, using the measured values from the experiments. In the second row of the table the equation of each of the geometries is compared with the 2D case. In the second and third row of the table the derived exponents are compared to the corresponding parameter from Eq. (2.13) and Eq. (2.19).

From Table 5.1 it can be observed that measured values do not agree with the existing formulas. A significant conclusion that the data in Table 5.1 denotes is that the exponent values correlated to three geometries with $\theta = 60^\circ$, 75° and 90° are close together (even the exponent values corresponding to $\theta = 30^\circ$, 45° are close to the same parameter in the 3D case). This finding should be considered in further studies. Since it may be possible to deduce that empirical equations for wave basin 3D can be applied to estimate parameters in general geometries where $\theta > 45^\circ$. ($\theta = 30^\circ$ is not included in this conclusion because although the proportional values are similar with the values for geometries with bigger side angles, wave behaviour in this geometry was different from other geometries).

Table 5.1 All geometries: comparison between exponents from Eq. (5.1), Eq. (2.13) and Eq. (2.19).

	Geometry									
	2D from Eq. 2.13	0° (2D)	15°	30°	45°	60°	75°	90° (3D)	3D corner	3D from Eq. 2.19
Exponent (n)	-4/15	-0.10	-0.43	-0.66	-0.65	-0.75	-0.74	-0.73	-0.41	-2/3
comparison with 2D from present study	NA	1	4.5	6.86	6.74	7.80	7.69	7.63	4.28	NA
comparison with 2D from Eq. 2.13 ($n/2D$)	1	0.36	1.62	2.47	2.43	2.81	2.77	2.71	1.54	NA
comparison with 3D from Eq. 2.19 ($n/3D$)	NA	NA	0.65	0.99	0.97	1.12	1.11	1.08	0.62	1

Table 5.1 also shows that the values for n Eq. (5.1) correlated to the 3D corner case and the 15° diverging geometries are similar. This finding may be a result of the dominant presence of reflective waves in these two geometries. Further investigation is required.

The information in Table 5.1 show that despite existence of non-negligible scale effects the exponent values corresponding to all geometries are more similar to the exponent values derived from Eq. (2.19) as compare with values in the first row of the table.

In general it may be concluded from Table 5.1 that effects of geometry on impulse waves are complex and it may be challenging or even impossible to express different effects of general geometries on wave parameter with a single equation.

The results from this table confirm the findings of Kinnear (2009). He recommended that the investigated reservoir geometries should be divided into three groups. The first group consists of wave basin and diverging reservoir geometries of 30°, 45°, 60° and 75° where the slide impact zone is uninhibited by a reservoir side (shoreline). The 30° diverging geometry is an exception to this conclusion since the results for $\theta = 30^\circ$ in this project does not agree with the corresponding parameters from Kinnear 2009.

A second group contains the 15° diverging reservoir geometry and slide impacting in the corner of the wave basin.

The third and final reservoir group is the wave channel geometry. In this situation impulse waves generated by subaerial landslides are confined by two reservoir sides as they

propagate. This results in larger maximum wave heights and smaller wave decays when compared to reservoir geometries in groups one and two (Kinnear, 2009).

5.2.2.3 COMPARISON WITH EMPIRICAL EQUATION OF HELLER ET AL. (2009)

In order to generalise the results of this study and to compare them with the existing equations, the measured relative wave heights for the 3D case are compared to the results from the empirical equation of Heller et al. (2009).

$$H(r, \gamma) = \left(\frac{3}{2}\right) P^{4/5} \cos^2\left(\frac{2\gamma}{3}\right) (r/h)^{-2/3} \quad \text{for } r/h > X_M \quad (5.2)$$

Where;

h [L] = Still water depth

H [L] = Wave height (Figure 4.1)

P [-] = Impulse product parameter (Eq. 2.4)

r [L] = Radial distance from the impact point (Figure 2.6(b))

X_M [-] = Relative streamwise distance from the impact location

γ [°] = Wave propagation angle (Figure 2.6(b))

Equation (5.2) is derived from Eq. (2.11) of Heller (2008) and Equation (2.16) of Huber and Hager (1997) and is based on the conversion method of Huber and Hager (1997). According to Huber (1980) it is possible to negate the difference in the height of impulse waves between 2D and 3D models in the slide impact zone. This statement was used in order to estimate wave parameters in a 3D model by using the results corresponding to a 2D model (Heller et al., 2009). Equation (5.2) is used in order to compare the measured relative wave height values in the 3D case of this study.

In this study only the parameter describing the wave propagations are considered in Equation (5.2) namely.

$$H(r, \gamma)/h = A \cos^2\left(\frac{2\gamma}{3}\right) (r/h)^n \quad (5.3)$$

Where $A = 1.67$ (A is parameter to shift the curves on the correct height) and n is the exponent derived from Table 5.1. Hence equation (5.3) converts to equation (5.4):

$$H(r, \gamma)/h = 1.67 \cdot \cos^2\left(\frac{2\gamma}{3}\right) (r/h)^{-0.73} \quad (5.4)$$

The same process has been done for the 3D corner case, using $A = 1.18$ and $n = -0.41$ from Table 5.1. The result is shown in Figure 5.5.

Figure 5.2 shows measured values of H/h as a function of γ correlated to the 3D tests in comparison with the results from equation (5.4).

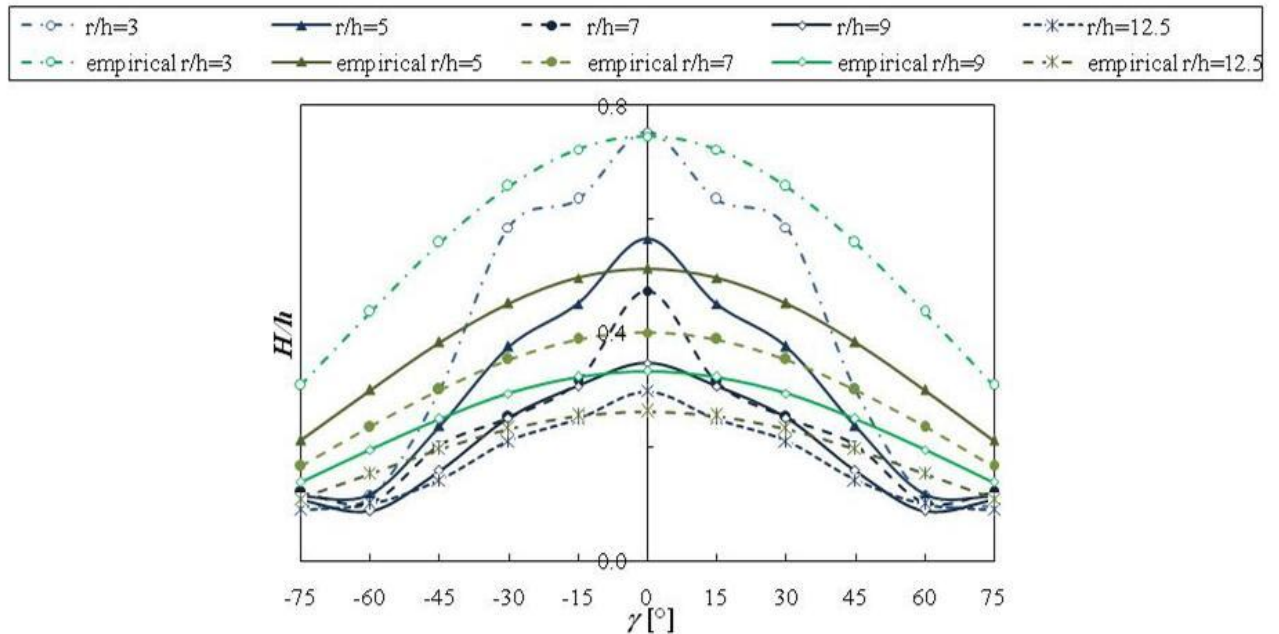


Figure 5.2 Wave basin: relative wave height as a function of wave propagation angle; comparison with Eq. (5.2).

Figure 5.2 illustrates that equation (5.4) overestimate the values for relative wave height corresponding to all the relative distances and all wave propagation angles except for $\gamma = 0^\circ$.

It is also observed that the calculated curves have a smaller slope compare to the measured values. It is identified that equation (5.4) underestimates the relative wave height decay as a function of wave propagation angle. In other words the decay term in equation (5.4) $\cos^2(\frac{2\gamma}{3})(r/h)^{-0.73}$ underestimates the decay rate of H/h in the wave basin. The deviation between measured and calculated values decreases as relative radial distance increase.

The chosen function ($\cos^2(x)$) may be the reason for this discrepancy. Hence the the measured and calculated data do not fit. Other functions (e.g. $\cos^3(x)$) may be more suitable for describing results in this case. Further studies need to be done in order to derive the suitable function.

Results from Figure 5.2 can be compared to studies of Huber and Hager (1997) and Panizzo et al. (2005a) (Figure 2.8).

Figure 5.2 shows relative wave height versus wave propagation angle corresponding to different relative distances and wave basin experiments.

5.2.2.4 COMPARISON OF THE EFFECTS OF THE DECAY TERMS (A) PANIZZO ET AL. (2005A) WITH AND HUBER AND HAGER (1997)

Figure 5.3(c) and 5.3(d) illustrates that the wave decay in the technical literature differs considerably according to Figure 5.3(a) and Figure 5.3(b). The reason for this discrepancy may be non-negligible scale effects and use of different block models and measurement methods (2.5). Also since Panizzo et al. (2005b) conducted the experiments in the corner of a wave basin assuming symmetry of the wave field, the results may have been affected by reflective waves and the decay for case shown in 5.3(c) and 5.3(d) are not the same (Section 2.5). The behaviour of the impulse waves in Figure 5.4(b) can be more similar to the corner case of this study rather than the 3D case.

Figure 5.3 compares relative wave height as a function of wave propagation angle from the study of Huber and Hager (1997) and Panizzo et al. (2005a) with the 3D case and the 3D corner cases of this project.

Figure 5.3 shows that the decay differs considerably between the three studies. Existence of non-negligible scale effects, different combination of governing parameters, different slide models, and differences in basin shape, effects of turbulence and water splash and use of different measurement methods may explain this discrepancy.

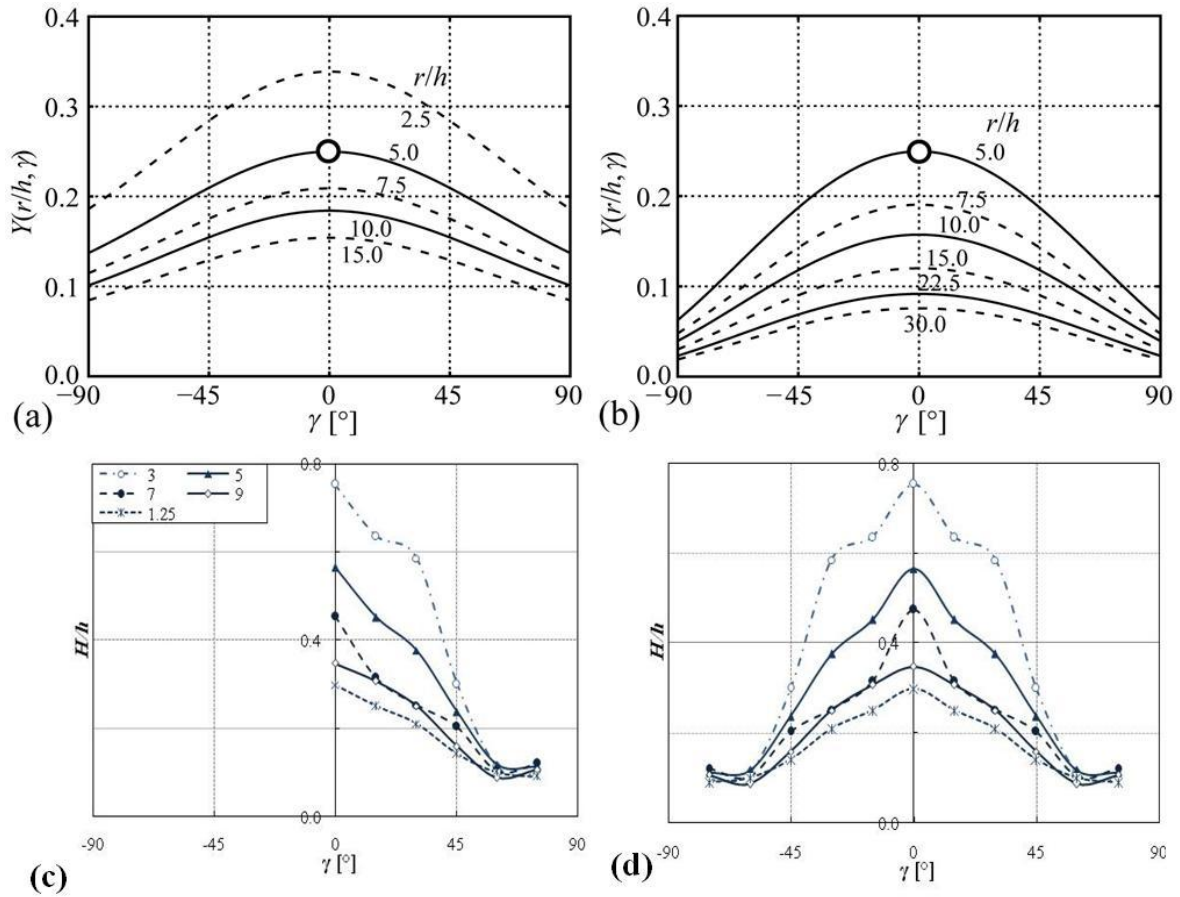


Figure 5.3 Comparison of the effects of the decay terms of (a) Panizzo et al. (2005a), (b) Huber and Hager (1997), (c) 3D corner case of the present study and (d) 3D case of the present study.

5.2.2.5 COMPARISON WITH GREEN'S LAW

According to Dean and Darlymple (1991) equation (5.5) can be used in order to define and calculate shoaling waves. (Shoaling: As the water depth decreases the height of shallow water waves increases whilst, at the same time, the wave length decreases (Heller et al., 2009)).

$$\frac{H_1}{H_2} = \left(\frac{h_1}{h_2}\right)^{1/4} \left(\frac{b_1}{b_2}\right)^{1/2} \quad (5.5)$$

Where

b_1 [L] = reservoir (channel) width at cross section 1

b_2 [L] = reservoir (channel) width at cross section 2

h_1 [L] = still water depth at cross section 1

h_2 [L] = still water depth at cross section 2

H_1 [L] = wave height at cross section 1

H_2 [L] = wave height at cross section 2

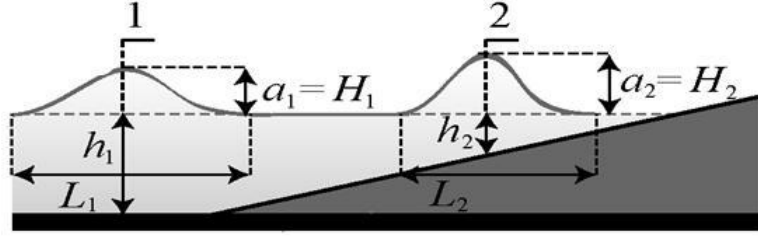


Figure 5.4 Shoaling of a solitary wave close to the shore with $a_1 < a_2$ and $L_1 < L_2$
(Heller et al., 2009)

Studying shoaling is out of aims of this study but a simplified form of equation (5.5) can be applied in this project. In case of a channel with diverging or converging breadth width since the still water level is constant and $\left(\frac{h_1}{h_2}\right)^{1/4} = 1$, as a result equation (5.6) is derived:

$$\frac{H_1}{H_2} = \left(\frac{b_1}{b_2}\right)^{1/2} \quad (5.6)$$

This equation which is also known as Green's Law and is based on constant energy flux between the cross sections. Measured relative wave height values for the geometries with $\theta = 15^\circ$ and 30° are compared to obtained values H_2 from Green's law.

In order to this H at each of the wave probes is calculated, as H_2 , by applying Green's law where the width of the wave channel (0.25 m) is considered as b_1 , the value of relative wave height corresponding to 2D, at the same relative distance, as H_1 , and width of diverging channel, as b_2 .

As an example process of computing relative wave height H_2 for $\theta = 15^\circ$ at $r/h = 5$ is presented as followed:

b_1 : Channel with corresponding to the 2D case = 0.25 m (constant)

H_1 : Relative wave height at $r/h = 3$ for 2D = 0.062 m

b_2 : Channel width at $r/h = 5$ corresponding to 15° diverging geometry = 0.52

$$\frac{0.062}{H_2} = \left(\frac{0.25}{0.52}\right)^{\frac{1}{2}} \Rightarrow H_2 = 0.041 \text{ m} \Rightarrow \frac{H_2}{h} = 0.41$$

The computed result can be compared with the measured value, which in this case is 0.37.

Same process for the two geometries and all relative distances was performed.

The results are shown in Figure 5.7. It can be observed that Green's law overestimates the relative height in the wave propagation zone however Green's law underestimate the wave height in the wave generation zone.

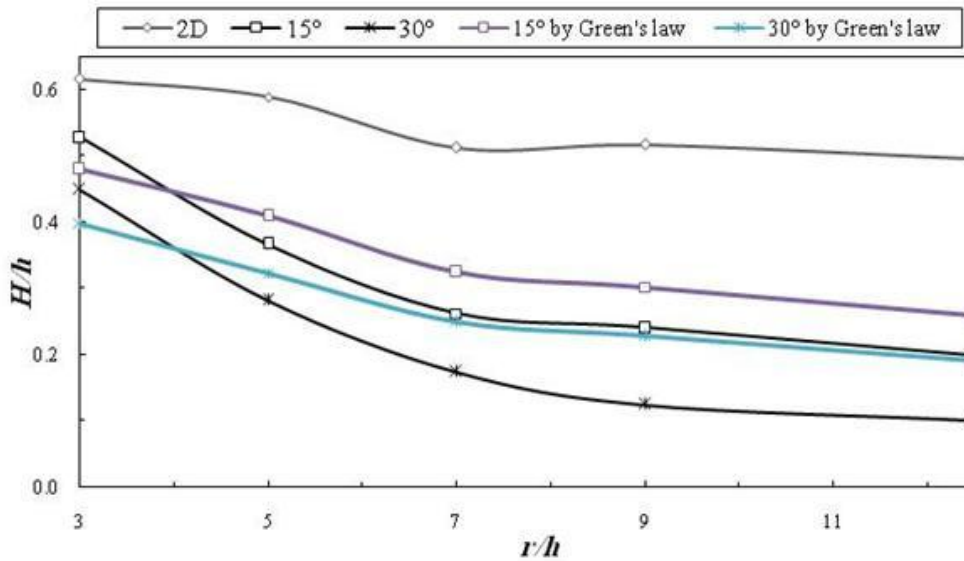


Figure 5.5 Relative wave height as a function of relative radial distance, comparison with Green's Law.

This has been previously done by Chang et al. (1979). Chang et al. (1979) conducted experiments in a channel of gradually varying width b and uniform depth in order to experimentally test the adiabatic approximation for a solitary wave. The results were numerically investigated by application of Korteweg-de Vries (KdV) equation. Results of this study show good agreement with KdV equation for the converging channel: $a \propto b^{-2/3}$ and a good agreement with Green's law for the diverging channel: $a \propto b^{-1/2}$ (in case of solitary waves $a = H$ (Section 2.2)).

Figure 5.8 shows comparison between measured and computed wave amplitude in the study of Chang et al. (1979).

259. Note that a and x are normalized with respect to the water depth (Chang et al., 1979).

By comparing Figure 5.7 and 5.8 it can be identified that results of Chang et al. (1979) agree well with Green's law in contrast with results of this project. This can be explained by the physical differences and differences between the two projects. The reservoir side angles in this project are bigger than the expansion angle in the study of Chang et al. (1979), also the type of the impulse wave is different.

Occurrence of frequency and amplitude dispersion and turbulence due to slide impact in this project may be the reason for the discrepancies. Also Chang et al. (1979) studies well

developed solitary waves with controlled and repeatable generation conditions however in the present study the wave profile is not well developed.

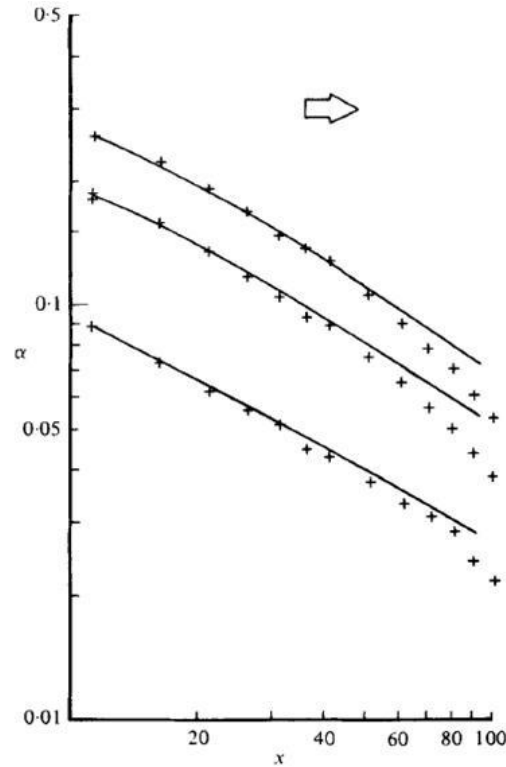


Figure 5.6 Measured (+) and computed (-) amplitudes a of a solitary wave in a diverging channel of expansion angle 0.019 radians (1.09°) and 0.2 m depth. The initial amplitudes are $a_0 = 0.088, 0.185, 0.259$.

5.3 WAVE AMPLITUDE

Figure 4.9 shows relative amplitude versus wave propagation angle for all geometries and for $r/h = 3$ and 5.

By comparing Figure 4.9 with Figure 4.6 it is identified that in general relative wave amplitude follows a similar trend as the relative wave height. Similar reasons as described in section 5.2 may explain this behaviour.

Characteristic for highly non-linear waves is the large difference between the wave crest and the wave trough amplitudes. Predicting solely the total wave height H is insufficient and misleading to characterize impulse waves (Fritz et al., 2006).

In order to study behaviour of troughs in different geometries a/h as a function of relative distance from the impact point is studied.

Figure 4.7 shows relative wave amplitude decay as a function of relative distance and Figure 4.8 shows a/H as a function of relative distance.

In Figure 4.8 effect of wave crests is not included in wave height and wave trough solely can be studied.

Comparing Figures 4.7 and 4.8 shows that a/H follows a more logical trend than a/h . This identifies that in this project wave troughs have a significant effect on the wave behaviour and change with change of θ .

It can also be observed that deviation between a/H values at different wave probes for all geometries (especially 2D and 30°) is much smaller than the deviation of a/h . This identifies that the size of wave troughs varies significantly with the relative distance from the impact point.

Figure 4.8 illustrates that wave troughs decreases as the reservoir side angle increases.

5.4 WAVE PERIOD

Figure 4.11 shows relative wave period $T_r = T/(g/h)^{1/2}$ as a function of wave propagation angle for all geometries.

It can be observed that wave period follow a more irregular trend compare to wave height and wave amplitude.

According to Heller et al. (2009) the correlation for wave period T is often worse than wave height and wave amplitude. However to calculate the effects of impulse wave on the structures wave period is less important than other parameters.

According to linear wave theory for intermediate water waves it is expected to see longer wave periods as the wave height decreases (and respectively wave length increases). This project investigated intermediate water waves however an impulse wave is not considered as a linear wave, hence it shows different behaviour. However linear wave theory can be applied for simplification. This is not always the case in Figure 4.11. The reasons for these irregularities may be explained by the complication process of wave generation with presence of turbidity, vortexes and air entrainment.

Relative wave periods follow a more regular trend in Figure 4.11(b) since the wave is more developed in this stage. However still some irregularities and sudden changes can be

observed. These discrepancies may be justified by occurrence of edge wave and reflective waves at some of the wave propagation angles.

5.5 SUMMARY

In this chapter the results were discussed. It is generally expected for relative wave height (and relative wave amplitude) to decrease as the reservoir side angle increase. The relative wave height and relative wave amplitude do not generally follow this expected trend.

In this chapter in attempt to derive a general equation which include effect of geometry on wave parameters the relative wave height for different geometries were compared with each other and the 2D case. Also the measured relative wave height decays were compared to the computed values applying eq. (2.13) and (2.16).

Analysing results of this project identifies that for reservoir side angles bigger than 45° ($45^\circ < \theta \leq 90^\circ$) relative wave height (and relative wave amplitude) shows a similar behaviour. Also wave parameters corresponding to the 3D corner test and 15° may be studied using the same equations. This confirms findings of Kinnear (2009).

Wave height decay in the wave basin and the corner case in this study were compared to wave height decay from wave basins in the studies of Huber and Hager (1997) and Panizzo et al. (2005a). The decay terms in empirical equations derived from both studies underestimate the wave height decay of this project.

It was observed that Green's law overestimate the relative wave height values corresponding to 15° and 30° diverging geometries in the wave propagation zone. the reason for this may be that Green's law does not consider energy dissipation also the derived values are based on values from the wave channel (with considerably higher wave heights compare to 15° and 30° geometries).

It was observed that in this project wave troughs are influential in varying relative wave height and behaviour. Also the size of wave troughs decrease as the reservoir side angle increases.

In this project it is observed that correlation of wave period is more challenging than other wave parameters.

Detailed conclusions from this study are presented in the following chapter.

6 Conclusions and Recommendations

6.1 INTRODUCTION

In order to study the effects of geometry on characteristics of subaerial landslide generated tsunamis a total of 168 experiments were conducted in a wave basin in the Hydraulics Laboratory of the University of Southampton. The tests were performed using a block model to simulate the landslide. The still water depth was kept constant through all experiments. Different diverging geometries were formed by placing vertical plexiglass walls inside the wave basin with different side angles θ . 8 different geometries were studied in this project including tests in the wave channel 2D ($\theta = 0^\circ$), the wave basin 3D ($\theta = 90^\circ$), 5 different diverging geometries with $\theta = 15^\circ, 30^\circ, 45^\circ, 60^\circ$ and 75° and finally a 3D corner test (where the slide was released into the water at the corner of the wave basin). This study is based on a pre-study by Kinnear (2009).

6.2 CONCLUSIONS

Overall it was observed that wave parameters such as wave height, wave amplitude, and their decays, wave period and the increase of it, are highly affected by geometry of the basin.

According to Huber (1980) the difference in size of impulse waves between 2D and 3D models in the slide impact zone is small. Results of this project show a good agreement with the above statement. Relative wave heights H/h in the wave generation zone (at $r/h = 3$) was measured as 0.62 for both wave channel and the wave basin. However this parameter differs by 25% near the wave propagation zone (at $r/h = 5$).

In this project impulse wave in the 3D case had its maximum at $\gamma = 0^\circ$, namely in the slide propagation axis. This is in agreement with of Huber and Hager (1997) and Panizzo et al (2005a). The maximum of wave height and wave amplitude was generally observed for a wave propagation angle γ between -15° and $+15^\circ$ for all geometries.

It was expected to that relative wave height H/h (and the wave amplitude a/h) decrease with increasing the reservoir side angle θ . However this was not observed for all geometries in this project and wave parameters follow an inconsistent trend.

Despite irregularity, it was observed that in geometries with reservoir side angle larger than 45° ($\theta = 60^\circ, 75^\circ$ and 90°) impulse wave characteristics are similar and the wave

parameters follow a similar trend. Also waves behave in a similar way in the 15° diverging geometry and the 3D corner case. The results of this project also show that wave parameters in the wave channel are significantly different from other geometries, since in this case the wave is completely confined by the two channel sidewalls and the wave propagates significantly different than the other geometries. These findings were previously noted in the study of Kinnear (2009) who had divided the geometries into three groups namely a) wave channel, b) 3D corner and 15° diverging channel, and c) 3D and reservoirs with side angle bigger than 45°.

Equations derived from 2D model investigations may be more applicable in wave channel reservoir geometries, and formulas derived from 3D model investigations to wave basin reservoir geometries (similar studies have been calculated by Heller et al., 2009).

In this project the results from the 30° diverging geometry may be highly affected by reflective waves and probably poor alignment and sealing of the transition, hence the results from experiments for this geometry are excluded from the general conclusions.

Generally it is concluded that effects of geometry on impulse wave parameters are highly complicated and cannot be described by use of a single equation.

Relative wave height as a function of wave propagation angle for the wave basin was compared with the corresponding parameter from the study of Huber and Hager (1997) and Panizzo et al. (2005a). This comparison identifies that the empirical equations from both studies underestimate the relative wave height decay with the wave propagation angle in the present study.

It was observed that Green's law underestimate the values of wave height corresponding to 15° and 30° diverging geometries in the wave generation zone, and overestimate it in the wave propagation zone.

In this project the ratio a/H corresponding to the wave channel was measured as 88% which can be comparable with finding of Heller and Hager (2010).

It was observed that in case of highly nonlinear impulse waves, wave troughs have a dominant effect on the size of the wave height and also the behaviour of the impulse wave correlated to different geometries. In this study the wave trough decreased as the reservoir side angle increased.

In order to present comprehensible conclusion about findings of this study further studies are required.

6.3 *RECOMMENDATIONS*

In this section some solutions for improving the physical model are presented.

In order to increase the repeatability of the experiments it is recommended to conduct the experiments in a short time after the calibration process. The quality of water affects its conductivity and this can highly change the result of the experiments. Also formation of air bubbles around the wave probes affects the conductivity between the metal bars of the probes which also affect the results. The formation of air bubbles increases with time.

It is also recommended that all experiments belonging to a specific geometry (e.g. different wave propagation angles) are conducted during a single day. This will make the data sets more comparable since for the probes have similar calibration values the quality of water is the same and the transition is in the similar condition.

The function of the transition is highly influential on repeatability of the experiments. The transition should be well aligned and well sealed between the basin bottom and the slide slope. It also should be located flush on the slide slope and in order to minimise effect of friction it should be clean and smooth on its surface.

It is recommended to use other software (in contrast to Microsoft Office Manager, which was used in this study) with the ability of higher resolution zoom-in to be used for computing the slide impact velocity.

6.4 *FURTHER STUDY*

Further works can be done on investigating the function of the transition and the methods to make the experiments more repeatable.

Further studies in this area can be focused on time of underwater slide motion and its effects on size of generate impulse waves.

It may also be of interest to investigate occurrence of the reflective waves in the 3D corner tests and 30° diverging reservoir geometry. This can be link to further studies on presence of edge waves in the wave basin at high values of γ and in order to deviate between the two phenomena.

Also further studies can be focused on deriving a mathematical solution which computes effects of different geometries on impulse wave parameters.

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