Measurement of Impact Forces for Different Types of Tsunami Waves

By

Muhamad Akmal Bin Mohlis

15052

Dissertation submitted in partial fulfilment of
the requirements for the

Bachelor of Engineering (Hons)

(Civil)

FYP II January 2014

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Measurement of Impact Forces for Different Types of Tsunami Waves

by

Muhamad Akmal Bin Mohlis

15052

A project dissertation submitted to the

Civil Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons.)

(CIVIL)

Approved by,

____

(Assoc. Prof. Dr. Indra Sati Hamonangan Harahap)

UNIVERSITI TEKNOLOGI PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible to the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources and person.

(MUHAMAD AKMAL BIN MOHLIS)

ACKNOWLEDGEMENT

Alhamdulillah, praise be to Allah SWT, the Almighty and may Allah's peace and blessings be upon His servant and Messenger Muhammad and upon his family and Companions. Thanks Allah whom with His willingness for giving me the opportunity to complete the Final Year Project Dissertation Report.

I am glad to express my utmost appreciation to my Supervisor, Assoc. Prof. Dr. Indra Sati Hamonangan Harahap, for guiding and advising me throughout the period of this project. The special thank goes to him for becoming my source of inspiration by giving me valuable information, suggestions and guidance throughout my final year project and also in preparation and completion of the Final Year Project Dissertation Report

I would also to express my grateful to all Laboratory General Assistants for their concern on my learning and researching progress during the experimental work. I am very thankful to my fellow friends for helping and guiding me in making this project to be succeeded.

Thank you.

ABSTRACT

For the past few years, a lot of laboratory investigations have been done in order to investigate the behavior of Tsunami impact force. Based on past researches, waves from Tsunami came with a lot of ambiguous conditions. In order to predict the Tsunami waves condition specifically in wave's impact force, this project is carried out. Experimental tests have been performed in measuring impact forces from different types of waves generated by different solid blocks. In this project, the setup of experiment is taken based on sub-aerial landslide modelling which is one of the factors that can generate Tsunami waves. The setup of experiment used three (3) solid blocks with different volume to be slid into the water, steel platform that acts as a bed slope, concrete flume as a medium to generate waves, three (3) wave probes to investigate the wave profile and load cells to measure and record the impact forces. The depth of water, bed slope, height of slope are constant whereby volume of solid blocks used, shape of solid blocks and the wave elevations are the manipulated variable in this experiment. The responding variable in this experiment is the impact forces measured by the load cells.

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTOS

LIST OF GRAPHS

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Background of Study

Tsunamis have recently happened a lot in this world which had bring a large destruction to onshore structures. As for human side, it is not possible for human to stop directly the disaster from occurring according to current technological equipment as for now. Due to that, laboratory investigations are one of the most reliable ways to conduct a research specifically in determining the behaviour of the Tsunami impact forces.

Tsunamis can be defined as a series of ocean waves that are generated by large scale disturbances of the ocean. According to U.S. Department of Commerce, it was found out that 80 percent of Tsunamis are occurred within Pacific Ocean, "Ring of Fire", whereby it is an active geological area in which a tectonic plate is forced underneath each another resulting in sudden shift that can change elevation of sea floor very fast and thus create big waves.

Figure 1.0: Location of Ring of Fire (Source: Google Images https://volcanicisabel.files.wordpress.com/2015/01/the-ring-of-fire.jpg)

One of the factors that contribute to Tsunami is the occurrence of sub-aerial landslide. Sub-aerial landslide can create impulsive waves which is as similar as Tsunami waves. These impulsive waves are usually happened due to impulse that has been transferred into the water body caused by rock falls, landslide, debris impact or avalanche impact. Usually, impulsive waves are typically generated in lakes, reservoirs, sea, ocean, or continental shelves. These impulse forces can bring severe danger to infrastructures and humans.

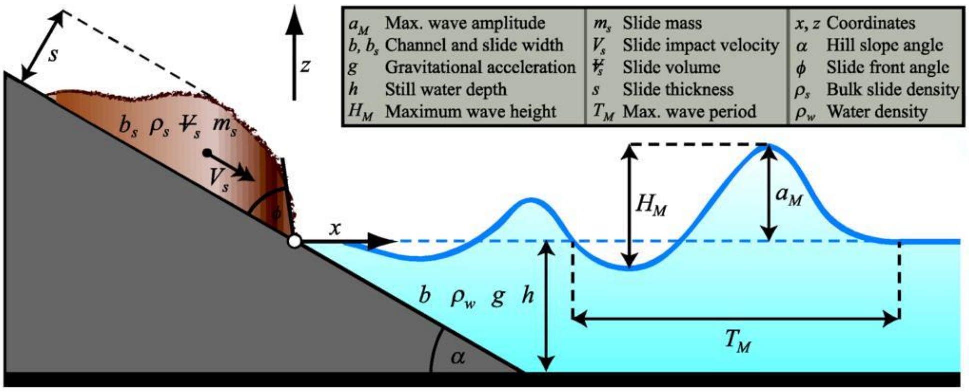


Figure 2.0: Sub-aerial landslide (Source: Google Images http://www.mdpi.com/jmse/jmse-02-00400/article_deploy/html/images/jmse-02-00400-g001-1024.png)

Scientifically, wave's impact force is a force that occurred or impacted on structures over a short period of time. This project is designed to assess the hypothesis that different type of waves will produce different behaviour of impact force. The trend of the magnitude of the impact forces created by Tsunami is very hard to predict. Hence, experiments and research on this scope of area is required in order to determine the pattern or trend of the results, mainly focusing in the impact force of the waves. Rationally, from the results obtained, mitigations can be further planned in order to reduce the bad impacts of Tsunami waves such as providing Tsunami evacuation structures or buildings for people that lived at the onshore in order to be safe from Tsunami.

1.2 Problem Statement

The destructions from Tsunami can cause long term effects to humans, animals, plants and infrastructures. Damage of plants and infrastructures, death, drowning or missing of human and animals are among of usual effects from Tsunami. In 2004, Tsunami waves with estimated height of 30 meter due to earthquake with a magnitude of 9.0 Richter scale were landed and destroyed the bordering of Indian Ocean. Of all 14 countries affected, about 230,000 people were died in that incident. Billions of costs were spent by the affected countries to recover their country.

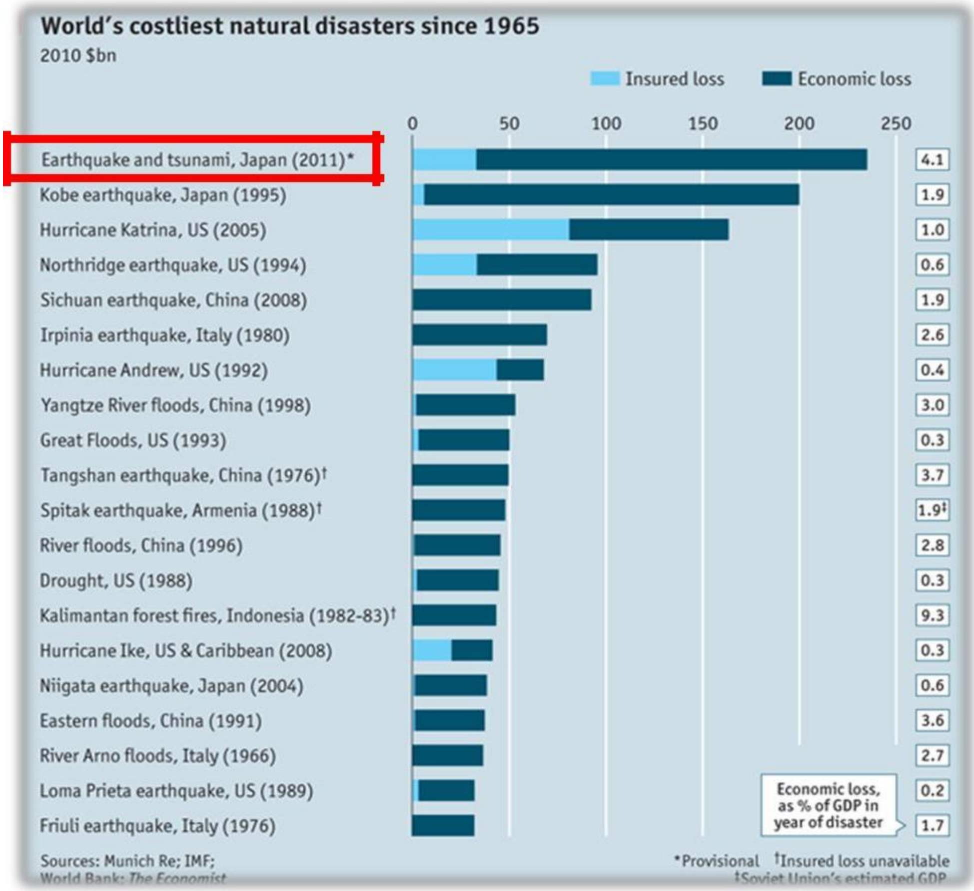


Figure 3.0: Statistic of natural disasters due to economic losses (Source: Google Images)

On top of that, this catastrophic Tsunami waves could bring such a big tremendous economic losses (Yeh 1991, Ghobarah et al. 2005, and Nistor et al. 2006). According to the World's Costliest Natural Disasters written by World Bank in 2012, Tsunami occurrence had bring an enormous economic losses towards the country, especially in Japan, in which, it was one of the worst Tsunami scenario happened to Japan in year 2011 whereby about 300,000 people who lost their homes were still living in temporary housing, two (2) years after the quake.

1.3 Objective and scope of study

The primary objective of this project is to investigate the behaviour of the impact forces from different waves generated in the experiment. Different types of waves are generated from different volume of solid blocks. From the different type of waves, the responding variable which is the impact forces obtained will be compared between the different waves generated. The result is then compared with Federal Emergency Management Agency (FEMA) guideline in P646A manual, entitled, *Guideline for Design of Structures for Vertical Evacuation from Tsunamis.*

1.4 Relevancy and Feasibility

The project is involving in investigating the behaviour of impact forces of Tsunami that are very ambiguous whereby the equipment and apparatus are available in the Offshore Laboratory in Universiti Teknologi PETRONAS (UTP). Only one elliptical solid block was require to be ordered from outside and the elliptical solid block was prepared according to the time. The experimental setup was progressing as planned even though there are several hiccups.

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Review on Standard Guidelines and Past Research Paper

In 2004, Indian Ocean Tsunami has landed to nearby coastline structures which had gave a large extensive impact and casualties due to big loading of waves to the structures constructed along the coastline. Fortunately, this tremendous event has increased awareness to structural engineers in designing structures to be able to withstand Tsunami wave impact (Yeh 1991, Ghobarah et al. 2005, and Nistor et al. 2006).

Federal Emergency Management Agency, FEMA, (2012) had published a guideline on design of structure for vertical evacuation from Tsunami. The objective of this guideline is to provide a short term protection from high risk Tsunami event. Building called vertical evacuation refugee is one of the methods that FEMA had come out that has an enough height in order to elevate and evacuate people at a safe height from Tsunami waves.

Besides that, Federal Emergency Management Agency, FEMA, (2011) had also published a guideline with two (2) volumes, in designing coastal structures, entitled, *FEMA Coastal Construction Manual*. Volume 1 of the manual provides a comprehensive description and approach in designing, constructing and maintaining onshore structures. While in volume 2 consist of detailed design, construction and maintenance practises to be followed.

Arikawa (2009) had published a study on structural behaviour of impulsive force due to Indian Ocean Tsunami incident. The study involving an investigation on surge front Tsunami forces by using physical modelling experiment. Different thicknesses of concrete wall ranging from 60 mm to 100 mm were used in the experimental setup. 2.5 m high of waves was generated by using paddle equipment. Results obtained shows that maximum impulsive force was occurred at the bottom of concrete wall with a force of 120 kN/m^2.

The study was concluded that the stronger the strength of the concrete wall, the failure mode will shift the failure to whole destruction of the wall. If the strength of the concrete wall is small, punching shear will be occurred at the concrete wall. It was added that the failure mode of the wall will be different according to the wall thickness.

2.2 Types of Tsunami Wave

As mentioned by Linton et al. (2012), there are three types of Tsunami force formations which are overflow (Type 1), bore (Type 2) and breaking (Type 3). In overflow formation, the velocity of flooding is low. It is elaborated by Oshnack (2010), reported that, as for bore formation, the flooding velocity is much quicker than overflow formation. In overall, breaking waves are the waves which have the highest flooding velocity and wave height.

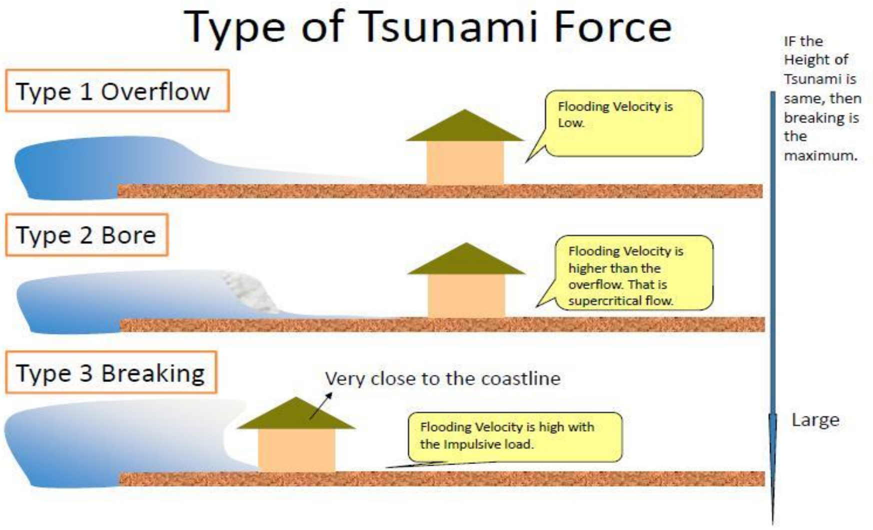


Figure 4.0: Type of Tsunami Force (Source: Google Images http://www.google.com.my/imgres?imgurl=https://metocean.files.wordpress.com/)

2.3 Tsunami Wave's Impact Behaviour

Nouri et al. (2007) had mentioned that load combinations are separated into two scenarios which are initial impact and post impact. The first combination occurs due to surge and debris impact forces. The second scenario considers the hydrodynamic (drag) and hydrostatic forces, simultaneously with the debris impact force. The forces involved will be summed up in order to calculate total Tsunami force.

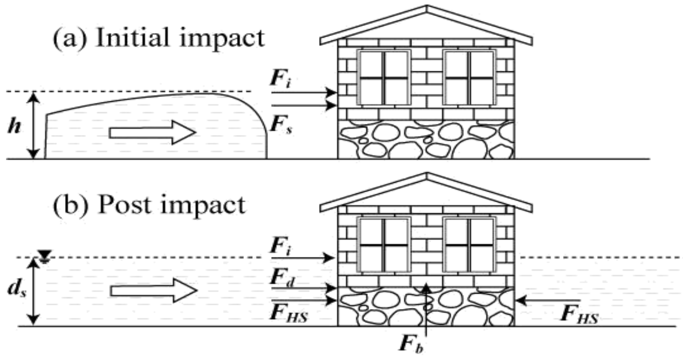


Figure 5.0: Forces involved before and after impact (Source: Google Images http://www.google.com.my/imgres?imgurl=https://metocean.files.wordpress.com/)

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

3.1 Research Tools

Internet resources: In order to have more understanding on the research's scope of study, journals and research paper had been accessed through the internet. Expected result, type of Tsunami forces and the behavior of the impact Tsunami forces were studied at first after the project's title is confirmed. After the result is obtained, the result is analyzed by referring to materials and videos from the internet.

Input from lecturers and Lab General Assistant: The author's supervisor had given the author some research papers for references in the beginning of this project. Formal and informal meetings were organized in order to discuss and understand the objectives in this research. In order to setup the experiment, lab general assistant had assisted the author very well from the beginning of the experiment until the result is obtained. The result was discussed with the lab general assistant in order to have justifications and understanding on result obtained.

3.2 Project's Flow Chart and Timeline

3.2.1 Final Year Project 1

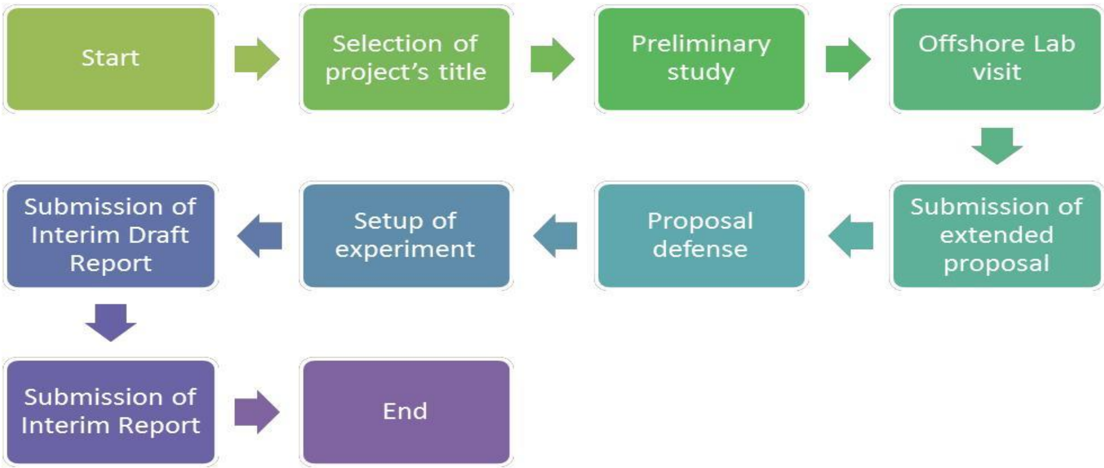


Figure 6.0: Final Year Project 1 Flow Chart

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic	■	■												
2	Preliminary Research Work		■	■	■	■									
3	Submission of Extended Proposal						●								
4	Proposal Defence								■	■					
5	Project work continues										■	■	■		
6	Submission of Interim Draft Report													●	
7	Submission of Interim Report														●

● Suggested milestone
■ Process

Figure 7.0: Project's Timeline (FYP1)

In Final Year Project 1, the author's supervisor, Assoc Prof. Dr. Indra Sati Hamonangan Harahap from Geotechnical Cluster in Civil Engineering Department had proposed this research to be carried out as a final year project. The project was begin with doing preliminary studies by reviewing past research with similar scope of study in this research. Offshore visit lab was then organized in order to have an overall view on the experimental equipment to be used.

Then, from the preliminary study and understanding on the research, a proposal needs to be prepared and presented for further understanding and improvements. First setup of experiment had been demonstrated after the proposal had been confirmed and finalized by the supervisor. At the end phase of FYP 1 timeline, an interim report needs to be submitted to the supervisor as a progress in FYP 1.

3.2.2 Final Year Project 2

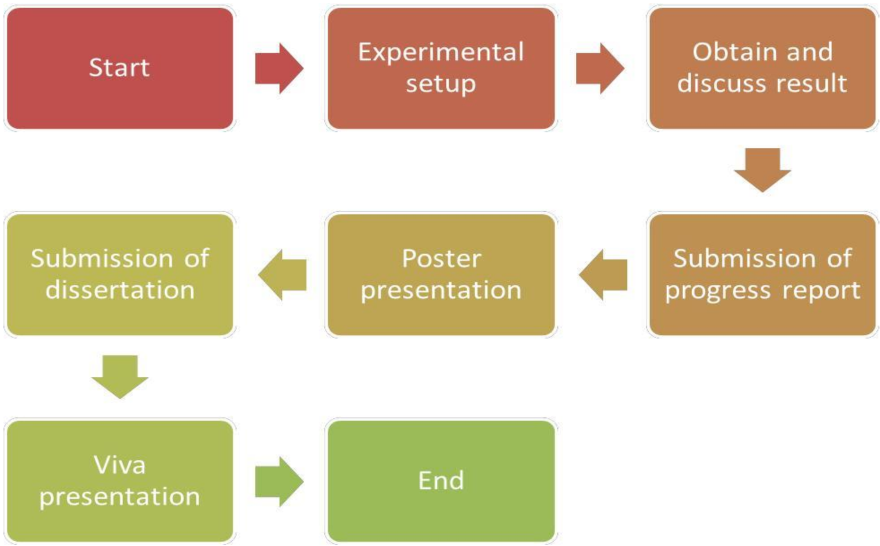


Figure 8.0: Final Year Project 2 Flow Chart

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continues	■	■	■	■	■	■	■								
2	Submission of Progress Report							●								
3	Project Work Continues								■	■	■	■	■			
4	Pre-SEDEX										●					
5	Submission of Draft Final Report											●				
6	Submission of Dissertation (soft bound)												●			
7	Submission of Technical Paper												●			
8	Viva													●		
9	Submission of Project Dissertation (Hard Bound)															●

● Suggested milestone
■ Process

Figure 9.0: Project's Timeline (FYP 2)

In Final Year Project 2, this phase is mainly focused in performing experiment and obtaining the result. From result obtained, analysis on the result has been done and need to be reported in the project's progress report. Abstract or summary of the project need to be presented to the lecturers in Geotechnical cluster in a poster presentation in order to have a full understanding and recommendation on the research.

3.3 Experimental Methodology

The experiment was performed and setup in Offshore Laboratory at Block J of Universiti Teknologi PETRONAS (UTP).

3.3.1 Experimental Program

The setup of experiment was carried out in a concrete flume of ten (10) metre length, 1.5 metre of width and one (1) metre of depth. The slope made with steel with a ratio of 1V:3H. Tsunami waves will be generated by sliding three (3) types of solid block with different volume and shape that are made with solid steel. The inclined slope was lubricant to reduce friction during the released of the solid blocks. There are three (3) wave probes were installed in this experiment in order to investigate the wave profile. The impact forces generated by the waves will be measured by two (2) load cells that were attached and tied on the steel platform.

In this experiment, the impact forces and the wave profile of solid block 1 (elliptical) was investigated initially, followed by solid block 2 (triangular) and solid block 3 (triangular). The inclined slope was at first lubricant by using oil spray to reduce the friction between the bottom of the solid block and the steel slope. All the 3 blocks were placed and positioned one by one on the steel inclined slope by using overhead crane. After the positioning of the solid block took place, the solid block will be hold by using two (2) ropes that had been hooked at the solid block. The ropes that were hooked with solid block were released and thus waves are generated. The wave's elevations were recorded by the wave probes and the impact forces of the waves were recorded by 2 load cells on left and right of the steel platform on the other side from the source of wave generation.

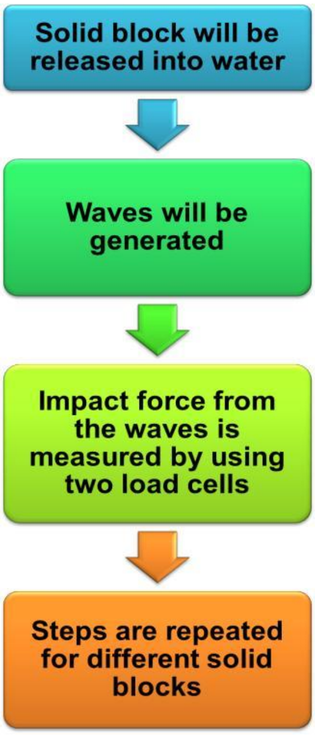


Figure 10.0: Experimental flow chart

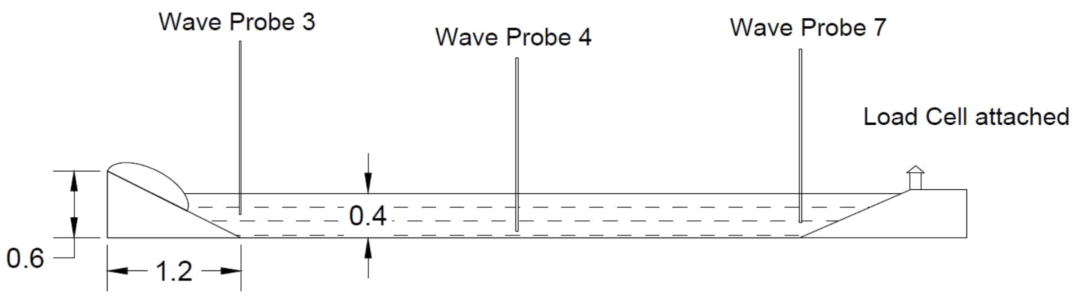


Figure 11.0: Experimental setup illustration

Photo 1.0: Concrete Flume

There are 3 types of solid blocks used in this experiment. Each solid block will be slid on the inclined slope in order to generate different type of waves. These generated waves will be the manipulated variable. In order to have different type of waves, different volume of solid blocks were used.

Model	Length (mm)	Height (mm)	Volume (m^3)	Shape
Solid Block 1	800	200	0.13	Ellipse
Solid Block 2	400	200	0.08	Triangle
Solid Block 3	200	100	0.02	Triangle

Table 1.0: Dimension of solid blocks

Photo 2.0: Solid block 1 (Elliptical) *Photo 3.0: Solid block 2 (Triangular)*

Photo 4.0: Solid block 3 (Triangular)

Two (2) load cells had been used in this experiment. Both of the load cells are located aligned (left and right) which are load cell 1 and load cell 2. The load cells are first calibrated and gave noise pattern in the graph. When the waves hit the load cell, the load cell will give and recorded a negative value of force due to the mechanism of the load cell in which compression force will measured as negative value.

Photo 5.0: Load cell (Front view) *Photo 6.0: Load cell (Side view)*

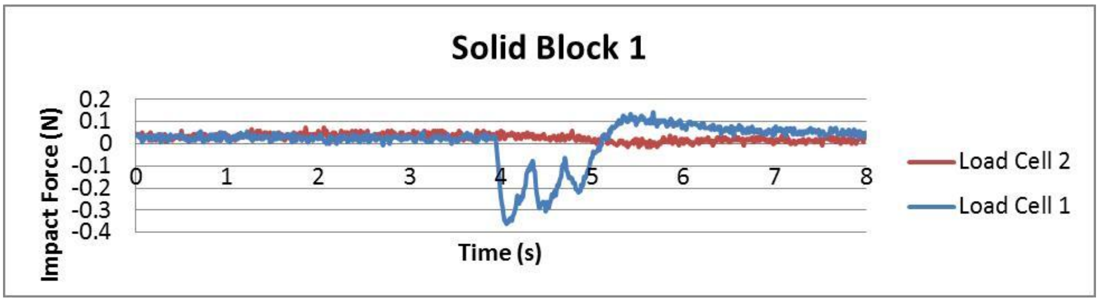
CHAPTER 4

RESULTS AND DISCUSSIONS

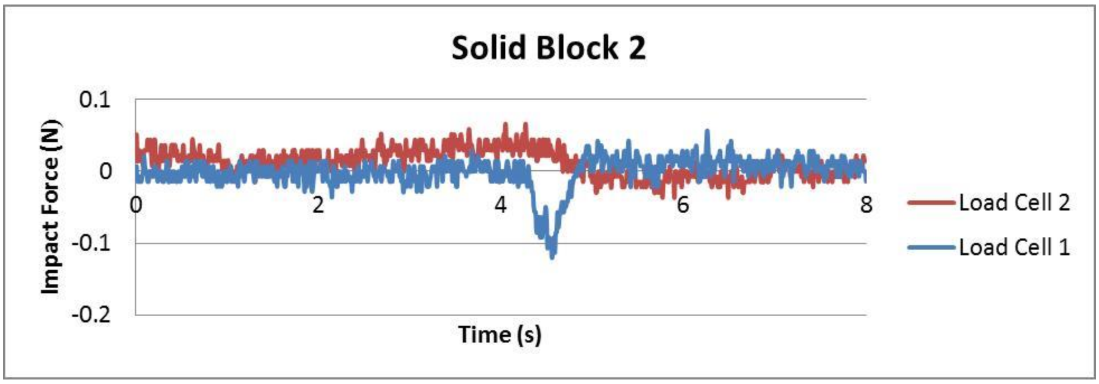
4. RESULTS AND DISCUSSIONS

In this experiment, three (3) trials had been performed for each solid block. A total of nine (9) data obtained and average of the data is calculated, tabulated and plotted in graphs.

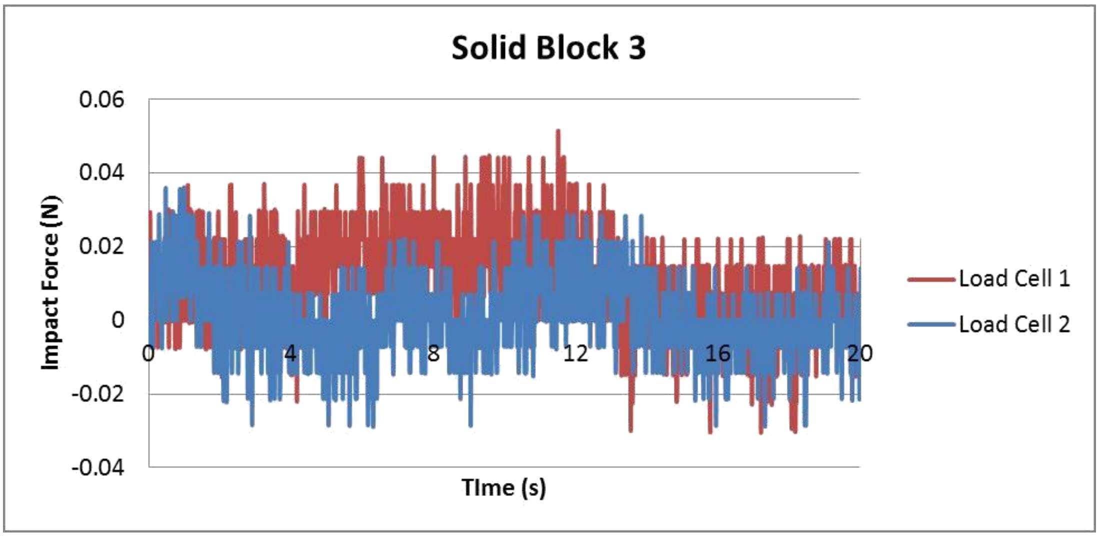
4.1 Data (Load Cell Equipment)



Graph 1.0: Force vs time of solid block 1 (Elliptical)



Graph 2.0: Force vs time of solid block 2 (Triangular)



Graph 3.0: Force vs time of solid block 3 (Triangular)

The negative values from the graphs showed the waves that had impacted the load cell. The compression from the waves impacted has been recorded by the load cell in negative value. The lower the impact force of the wave, the greater the compression force occur in this experiment.

From Graph 1.0, it was observed 3 waves had impacted the structure in thich the first wave that impacted the load cell 1 gave the largest impact force which is 0.3 N, followed by second wave in which the impact force is slightly less than the first wave. The trending of the forces from the waves are initially higher force, followed by lower force and force goes back increasing and decreasing until no force is impacted.

As for Graph 2.0, there are 2 waves impacted in overall and the first wave impacted the load cell 1 did not initially started with the highest force compared to force generated by solid block 1 (elliptical). The highest force occurred at the second wave.

In graph 3.0, it was measured that the forces generated by solid block 3 (triangular) is very small. The trending of impact force in the graph looks alike as similar as the noise pattern in the graph.

Model	Load Cell	Load Cell Reading (N)	Maximum Impact Force (N)
Solid Block 1	1	-0.01	0.01
	2	-0.3	0.3
Solid Block 2	1	-0.03	0.03
	2	-0.1	0.1
Solid Block 3	1	-0.02	0.02
	2	-0.02	0.02

Table 2.0: Summary of maximum load cell reading

	Discussions
Graph 1.0	Initial overshoot of impact force is observed with a maximum of 0.3 N at 4 seconds
Graph 2.0	Maximum impact force of 0.1 N is observed at before the waves hit the load cells
Graph 3.0	No significant overshoot in impact force due to small waves production

Table 3.0: Discussions on the graph

In overall, it was observed that all the waves generated are an overflow waves which has very low in velocity and wave height. It was found that the load cell for both sides which are Load Cell 1 and Load Cell 2 are not simultaneously received the wave's impact force in which both load cells supposedly had the same data of impact force. Due to that, it was assumed that there are some error happened during the release of the solid blocks in the first place.

The equation to calculate the impact force as stated by FEMA P-646 in Coastal Construction Manual is as below:

$$F_d = (1.5)\ ½\ C_d \rho v^2 A$$

Whereby C_d is drag coefficient which is equal to 2.0 for rectangular structure, ρ is the density of the water, A is the surface area of the square steel plate of load cell which is equal to 0.0023 m^2. There are three (3) experimental velocities that had been used by FEMA as stated by Al-Faesly et al. (2013) as per table below:

Theoritical data	
u (m/s)	Fd (N)
1.4	0.27
1.6	0.35
1.8	0.45

Table 4.0: Impulsive forces from different types of velocity of waves

From the Table 4.0, it can be seen that the sensitivity of the impact forces from different velocities are small in a range from 0.08 N to 0.10 N. This shows that impact forces are very sensitive to the velocities. The reason to use these three (3) velocities is that these velocities are in a range of steady state flow as mentioned in FEMA P55 Guideline.

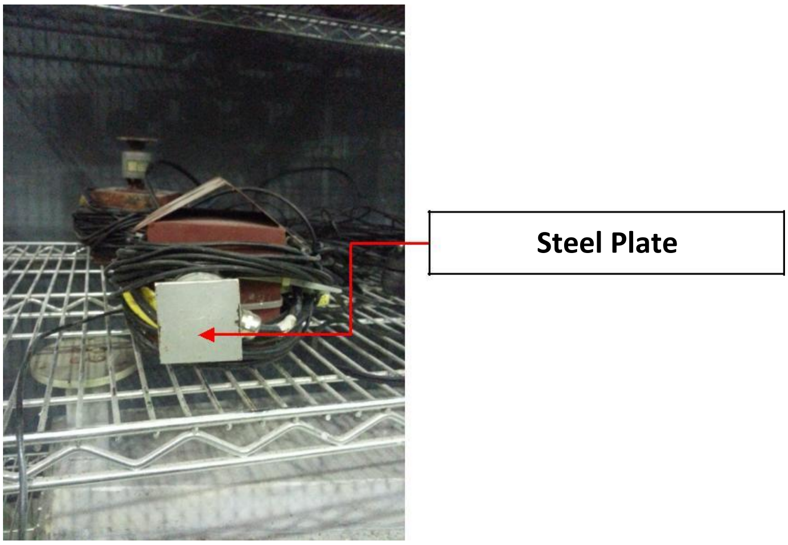


Photo 5.0: Area of the steel plate of load cell (0.48m x 0.48m)

The highest experimental impact force is then compared with the theoretical impact force calculated based on FEMA. The highest theoretical impact force is equals to 0.45 N which is higher than the experimental value which this experimental result is about 60 percent reliable.

4.2. Data (Wave Gauge Probe Reading)

Gauge 3 Gauge 4 Gauge 7

Block 1

Block 2

Block 3

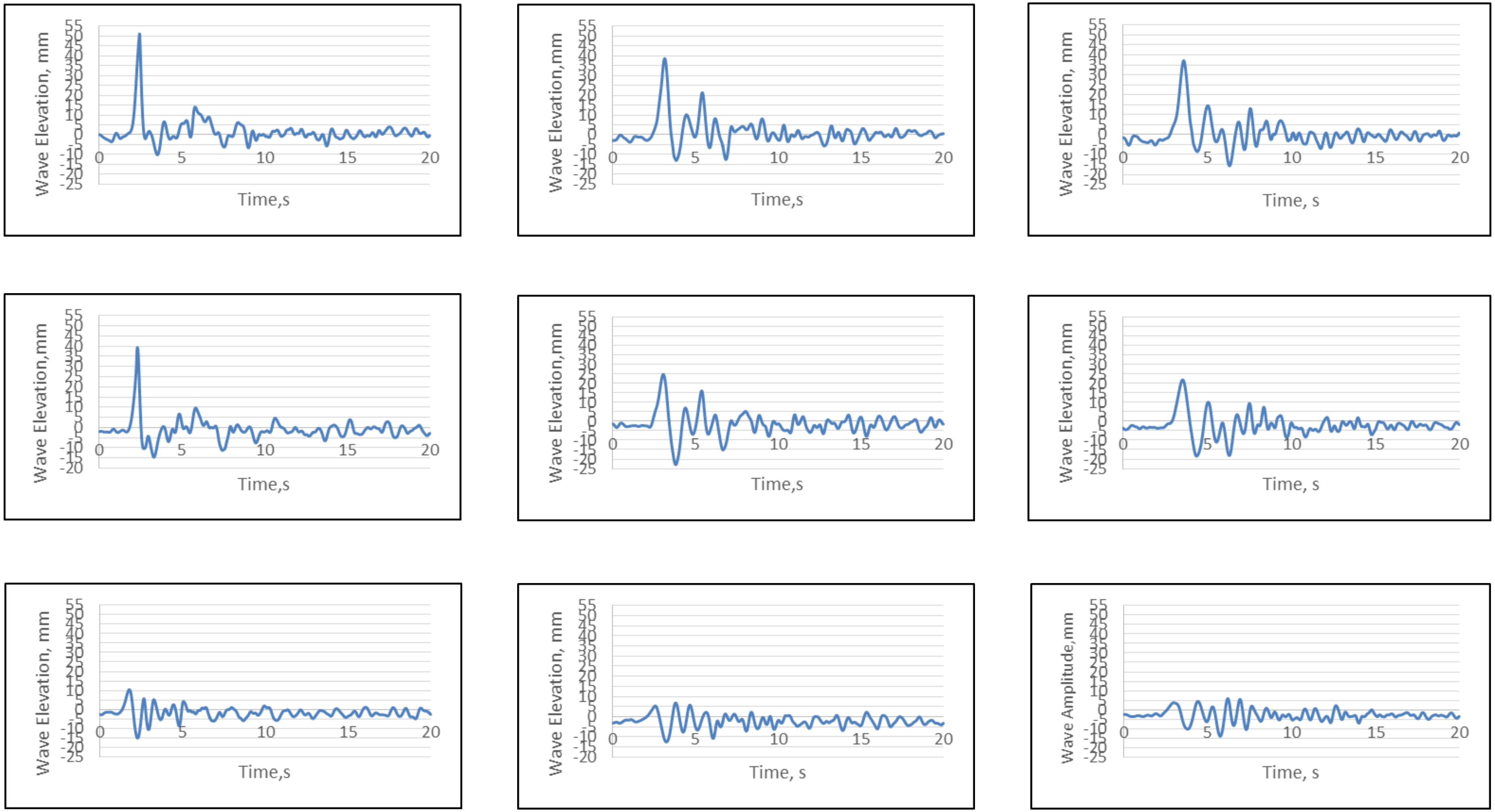


Figure 12.0: Graph of Wave Elevation against Time for three different solid blocks

Initially, there are eight (8) wave probes to be used in this experiment in order to increase the accuracy of the data. However, the other five (5) wave probes are malfunctioned. Hence, there are three (3) wave probes were installed at different location which are near the source of wave's generation, at the middle of the experimental medium and at the end or near the load cells. These wave probes were installed in order to determine the wave elevations from the sliding of the solid blocks.

From the data of the wave probes, it can be seen that the highest elevation occurred from waves generated by elliptical solid block in which it was experimentally observed that the wave was overtopped the structure that was attached with the load cell. In this part of experiment, from the result, it can be concluded that the wave elevation will be at its maximum at location which is near the source of generation of wave.

CHAPTER 5

CONCLUSION

5. CONCLUSION

Tsunami is one of great disasters happen that could bring such a disastrous scenario and nightmare to the world. Sometimes, Tsunami event is shockingly happen without any notice or sign that it will be happened. This would help the humanity to come out with a good preventive measure and recovery plan in order to reduce any unwanted scenario to be happened. It was concluded that the behaviour of the impact force generated by different types of solid block will generate different type of trending of impact forces. In addition, in terms of time constraint, this project is very feasible to be carried on with the assist of project's supervisor, coordinator and general assistant. In overall, elliptical solid block 1 has the highest elevation of wave and also contributes to the maximum of impact force compared to the others. It was found that the wave elevation will be the maximum near the source of wave's generation in which that wave will give a highest impact force.

CHAPTER 6

REFERENCES

[1] D. Linton, R. Gupta, D. Cox, J. van de Lindt, M.E. Oshback and M. Clauson, "Evaluation of Tsunami Loads on Wood-Frame Walls at Full Scale" in Journal of Structural engineering, vol. 139, 8th ed. 2012, pp. 1318-1325

[2] FEMA P646, "Guidelines for Design of Structure for Vertical Evacuation from Tsunami," Federal Emergency Management Agency, Washington, D.C., 2012.

[3] Grilli. S. T. & Watts. P. (2005). Tsunami generation by submarine mass failure. I: Modeling, experimental validation, and sensitivity analysis. *Journal of waterway, port, coastal and ocean engineering, 131 (6), 283-297.*

[4] Hampton. M. A., Lee. H. J., and Locat. J., (1996) "Submarine Landslides" in *Review of Geophysics,* Vol. 34, 1st Ed. Pp 2-3.

[5] Hiroshi Fukuyama, H. K. (2013). *Structural Design Requirement on the Tsunami Evacuation Buildings.* Tokyo: University of Tokyo.

[6] Michael Mohoney, R. D. (2008). *Guidelines for Design of Structures for.* Redwood City, California: Federal Emergency Management Agency.

[7] Nouri (2011, April 16). *Metocean*. Retrieved December 4, 2014, from Metocean: http://metocean.wordpress.com/

[8] Suguru Mizutani, F. I. (2001). *Dynamic Wave Force of Tsunamis Acting on a Structure.* Aoba, Japan: Disaster Control Research Center, Tohoku University.

[9] Tappin, D. R. (2010). *Submarine Mass Failures As Tsunami Sources: Their Climate Control.* British Geological Survey, Nottingham NG12 5GG, UK.

[10] Mary Elizabeth Oshnack, D. C. (2010). Analysis of Wave Forces on Prototype Walls under Tsunami Loading. *Cross Shore Variation of Tsunami Loading on Vertical Wall: Transition From Impulse Load to Quasi Steady Bores*, 38.

[11] Watts. P. " Tsunami features of solid block underwater landslide" in . *Journal of waterway, port, coastal and ocean engineering.* Vol. 126. 3rd Ed. P.144-152.

[12] Vashtag, B. (2011, March 11). *Japan a leader in engineering earthquake-proof structures, helping to limit damage*. Retrieved 12 4, 2014, from The Washington Post: http://www.washingtonpost.com/national/japan-a-leader-in-engineering-earthquake-proof-structure/2011/03/11/ABMF24Q_story.html

[13] Watts. P. & Grilli. S. T. (2003). Underwater landslide shape, motion, deformation, and tsunami generation. *Proceeding of The Thirteenth International Offshore and Polar Engineering Conference, Honolulu, Hawaii, 3, 364-371.*

CHAPTER 7

APPENDICES

7.1 Raw Data of Experiment

Findings

Legends / Indicators:

- **Model 1**: **Ellipse** solid block
- **Model 2**: **Triangle** solid block (Large)
- **Model 3**: **Triangle** solid block (Small)
- **Location of Channel 1**:At right side of platform
- **Location of Channel 2**: At left side of platform

Types of data and result

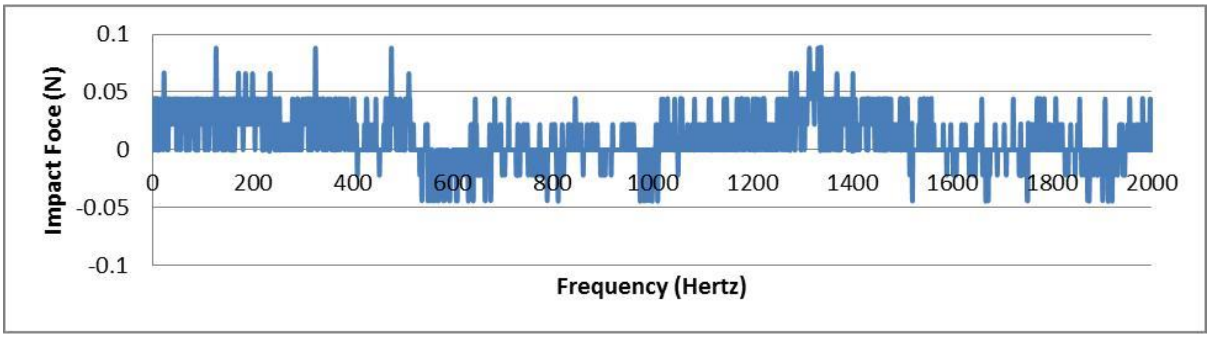
- From load cell equipment (Detect impact force every 10 milliseconds)
    i) Graph of impact force against time
- From wave probe equipment
    i) Graph of wave elevation against time

Data and Results

Graph of Impact Force against Time (Load Cell)

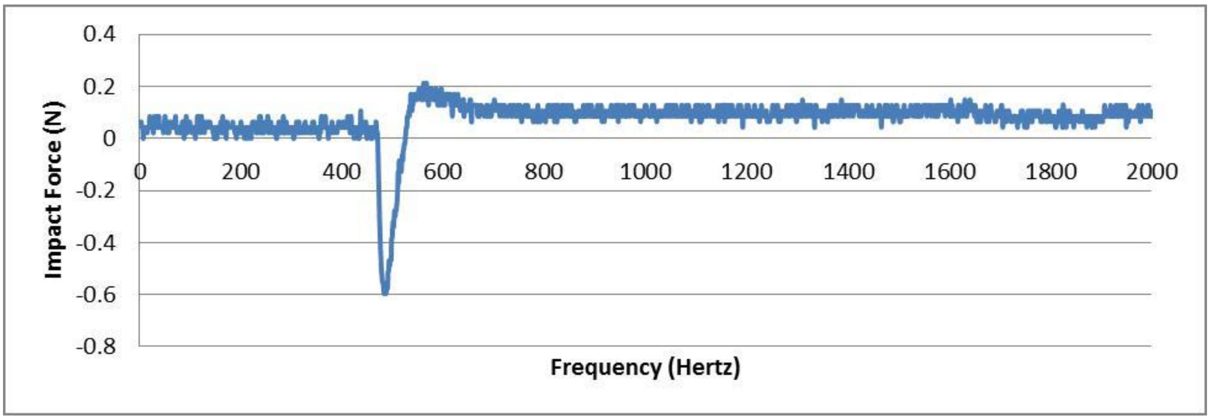
Model 1 (1st Trial)

Channel 1



Maximum Impact Force: 0.08824 N

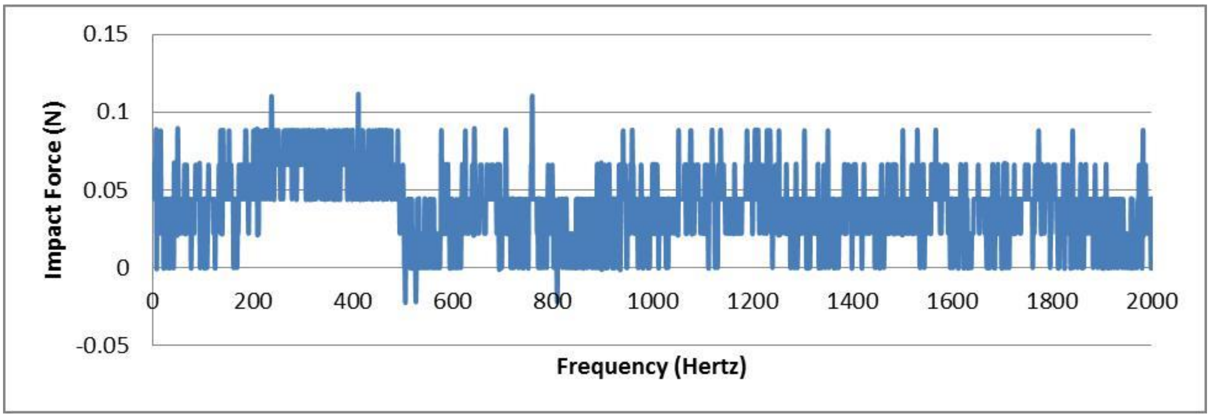
Channel 2



Maximum Impact Force: 0.21284 N

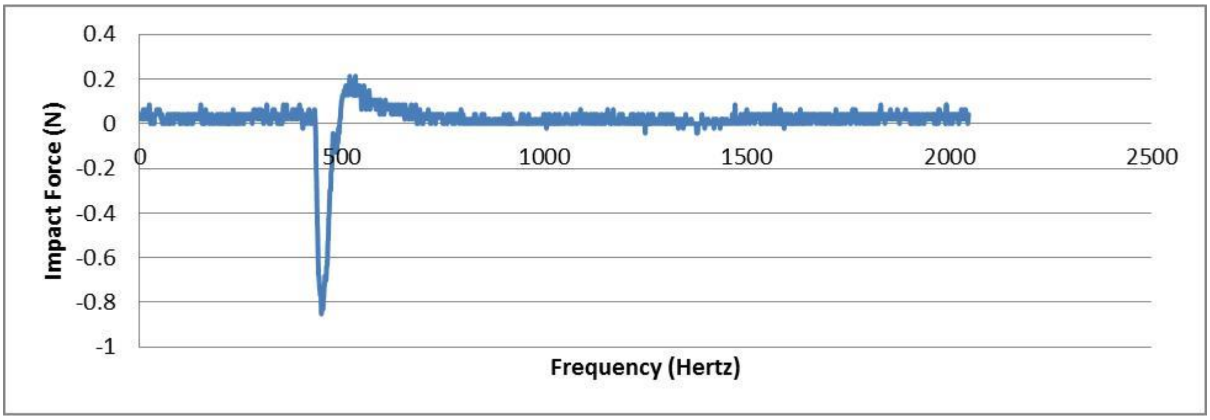
Model 1 (2^{nd} Trial)

Channel 1



Maximum Impact Force: 0.1103 N

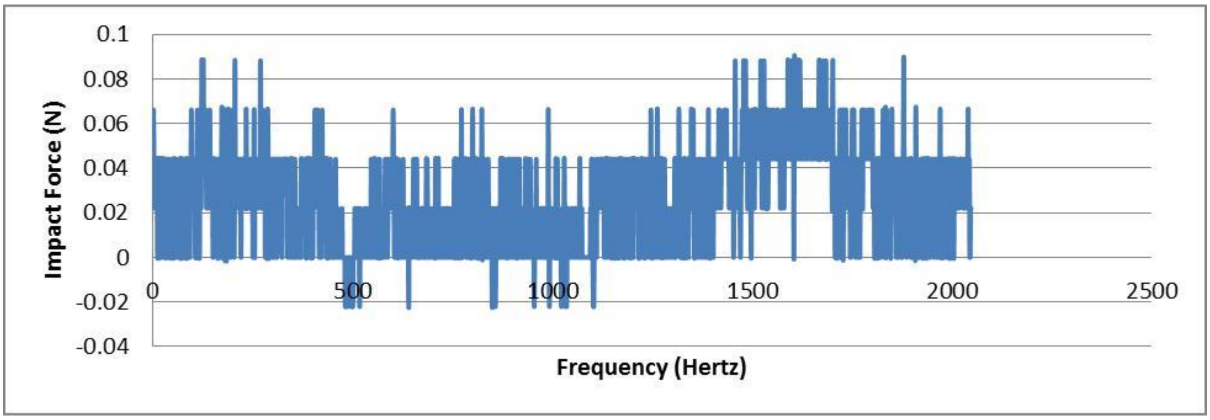
Channel 2



Maximum Impact Force: 0.21284 N

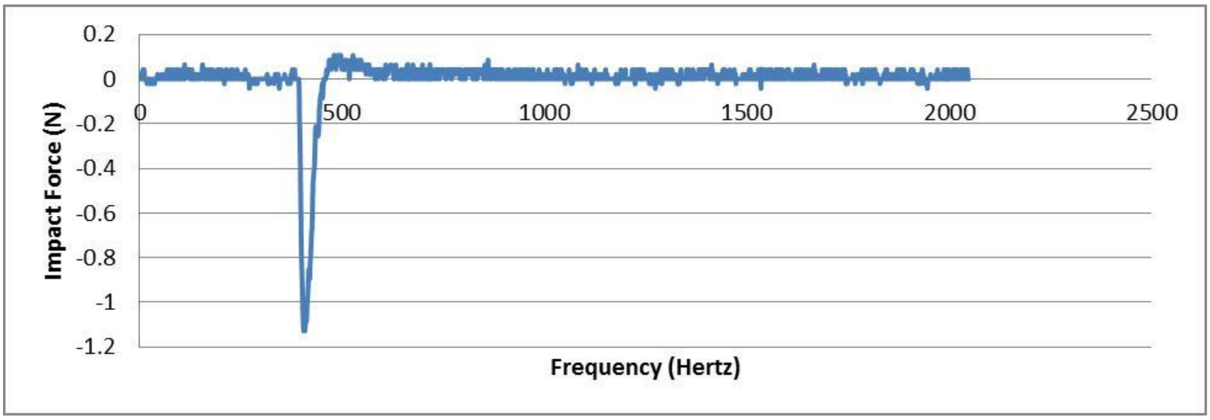
Model 1 (3rd Trial)

Channel 1



Maximum Impact Force: 0.08824 N

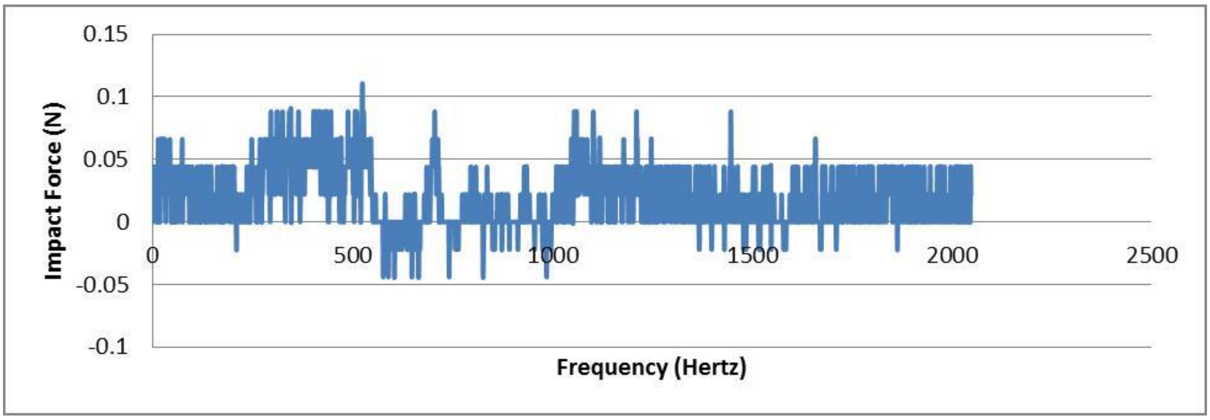
Channel 2



Maximum Impact Force: 0.10642 N

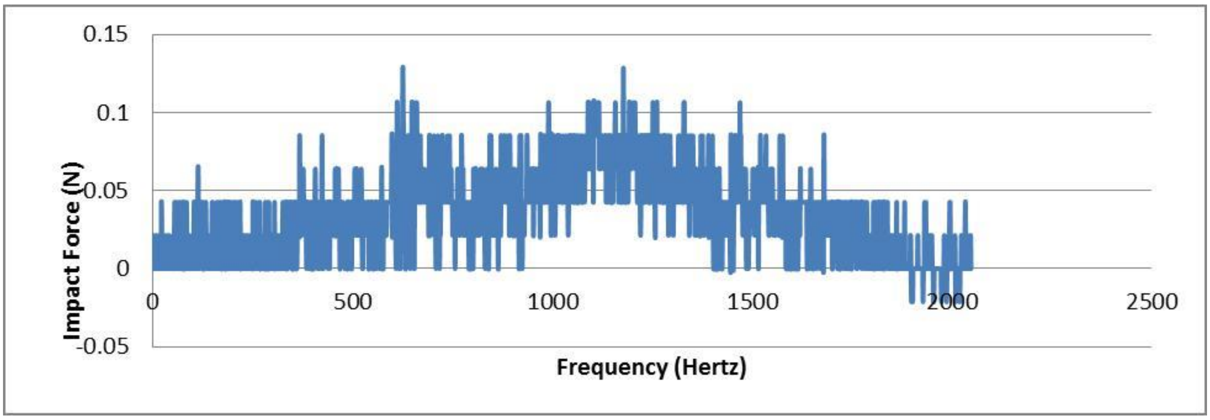
Model 2 (1st Trial)

Channel 1



Maximum Impact Force: 0.1103 N

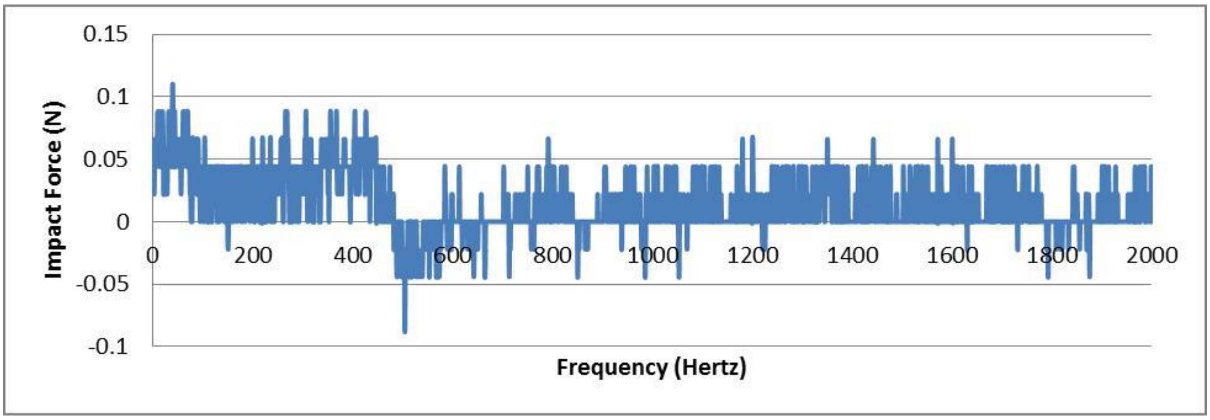
Channel 2



Maximum Impact Force: 0.127704 N

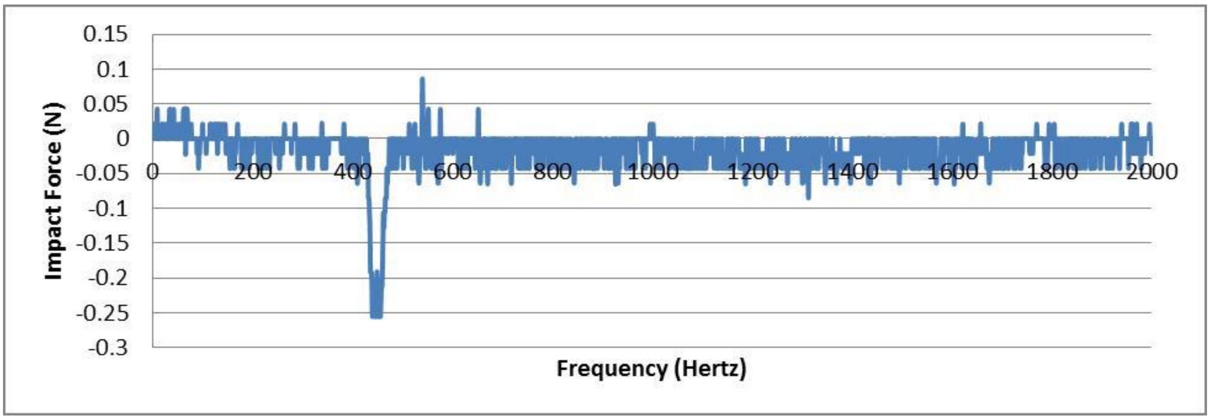
Model 2 (2nd Trial)

Channel 1



Maximum Impact Force: 0.1103 N

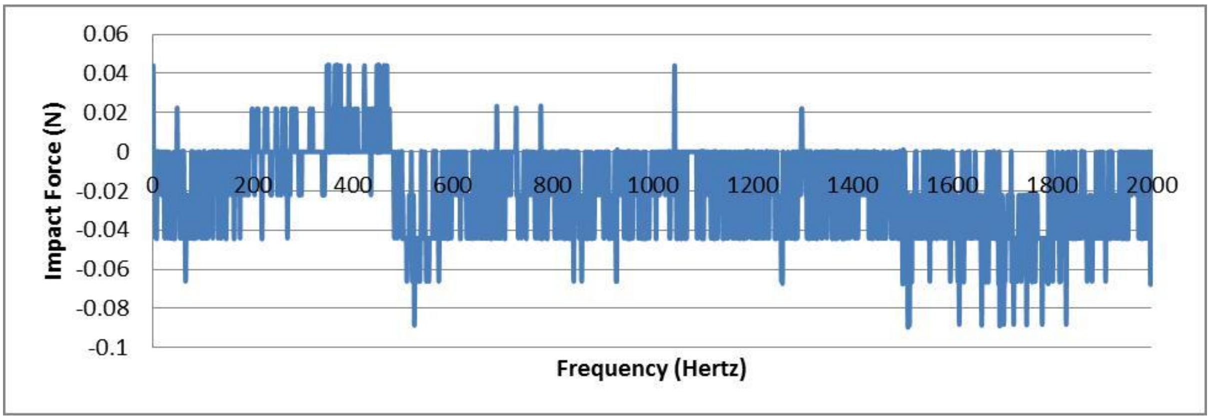
Channel 2



Maximum Impact Force: 0.085136 N

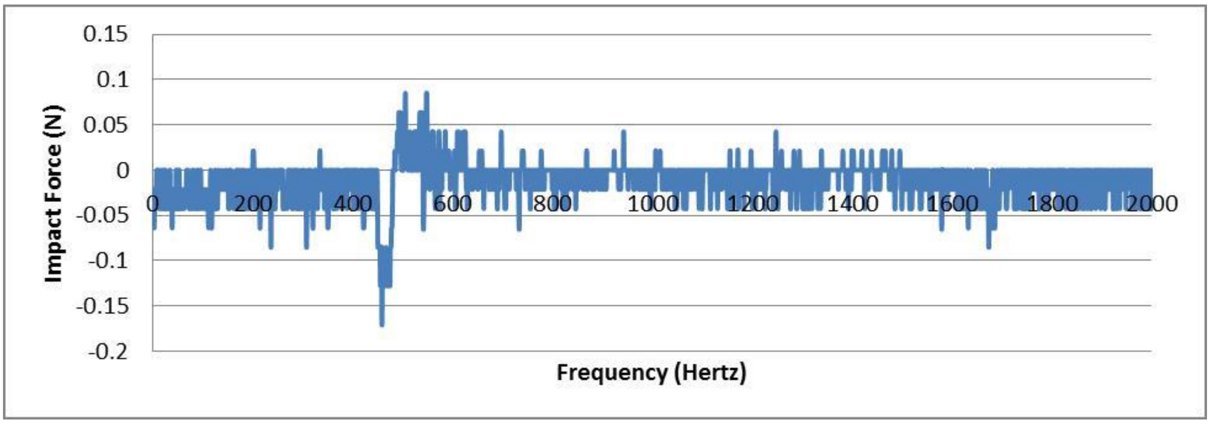
Model 2 (3^{rd} Trial)

Channel 1



Maximum Impact Force: 0.04412 N

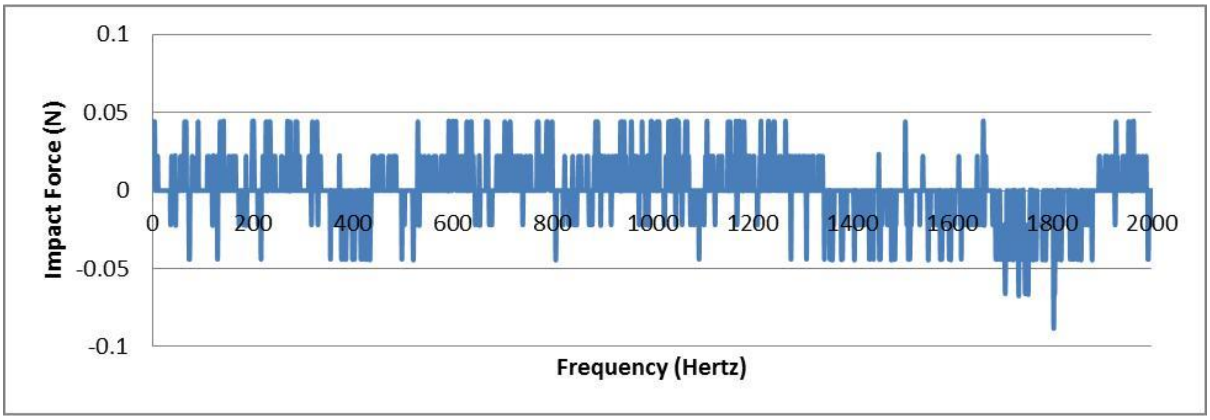
Channel 2



Maximum Impact Force: 0.085136 N

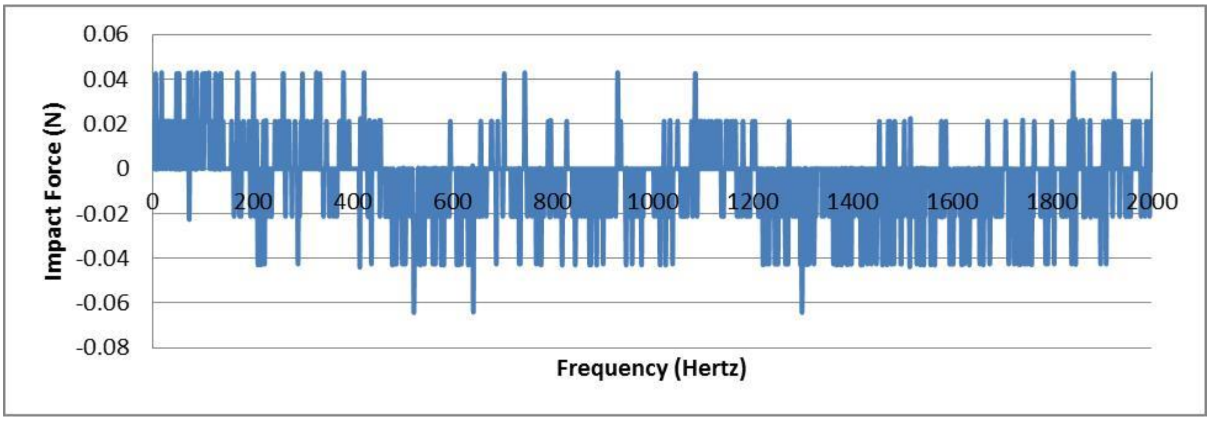
Model 3 (1st Trial)

Channel 1



Maximum Impact Force: 0.04412 N

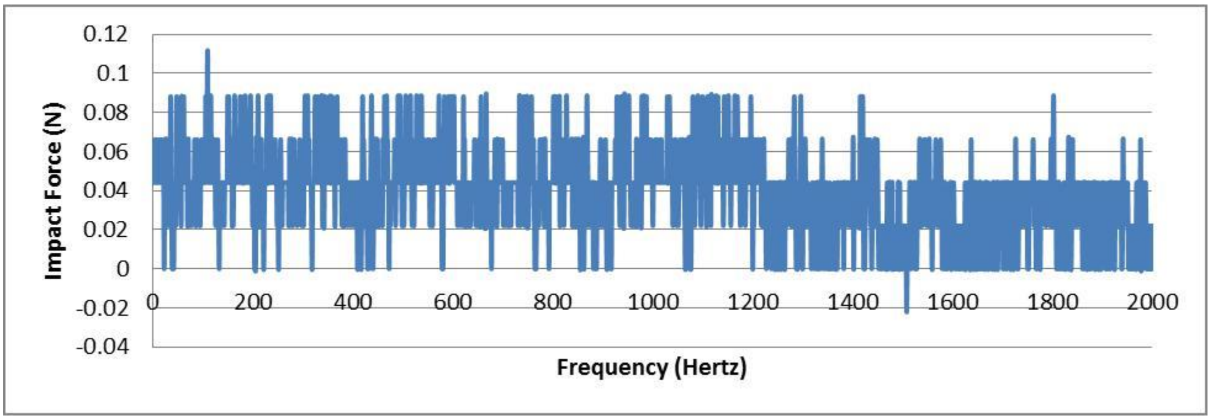
Channel 2



Maximum Impact Force: 0.042568 N

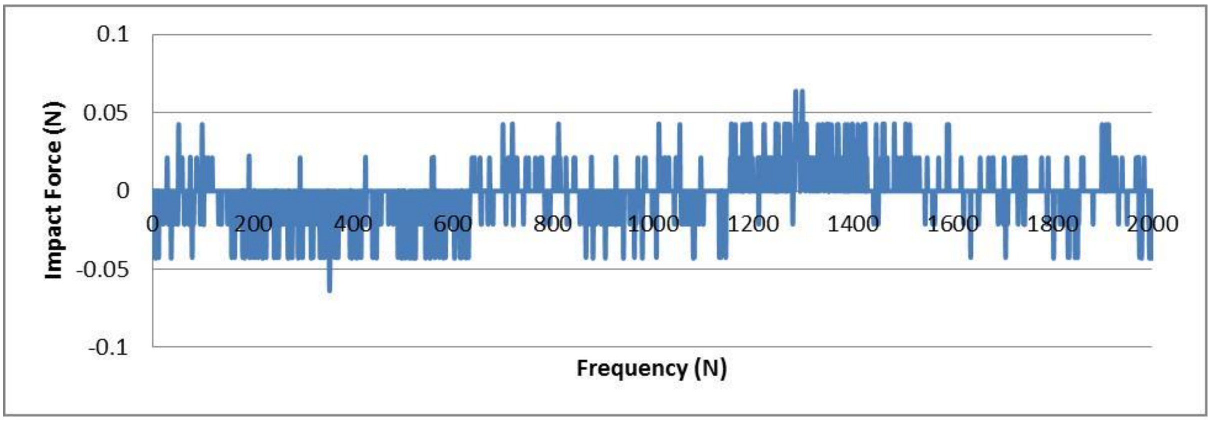
Model 3 (2^{nd} Trial)

Channel 1



Maximum Impact Force: 0.1103 N

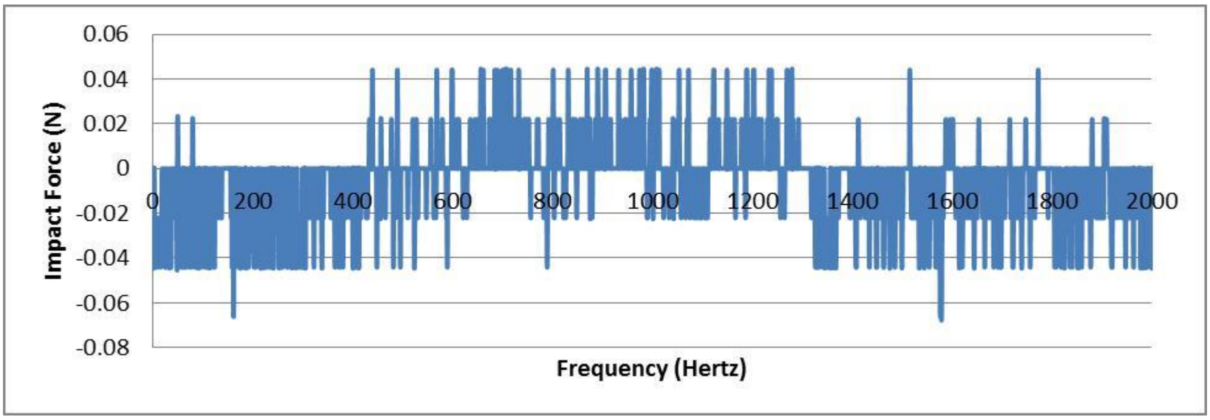
Channel 2



Maximum Impact Force: 0.063852 N

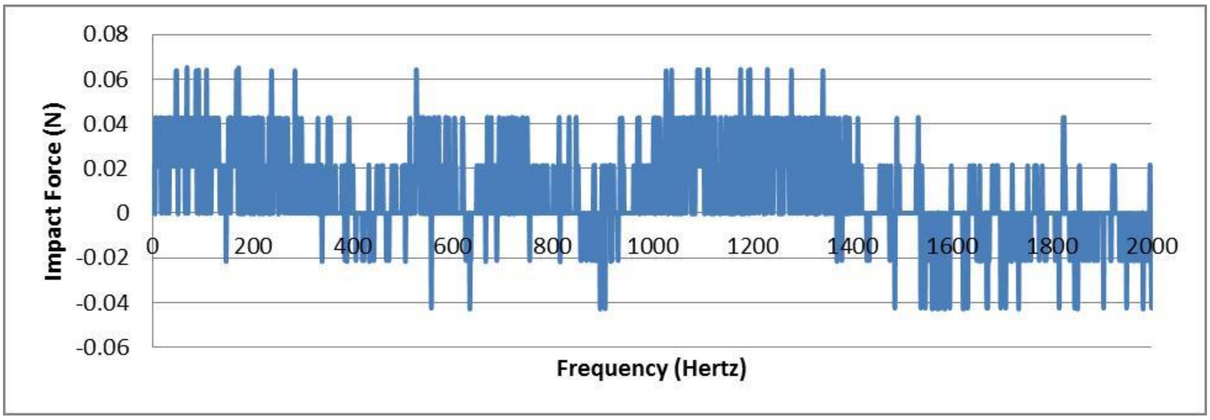
Model 3 (3^{rd} Trial)

Channel 1



Maximum Impact Force: 0.04412 N

Channel 2



Maximum Impact Force: 0.063852 N

Tabulation of data (From 3 Trials)

Model	Load Cell	Average of Impact Force (N)
Solid Block 1	1	0.0753
	2	0.141
Solid Block 2	1	0.0662
	2	0.0568
Solid Block 3	1	0.0514
	2	0.0354

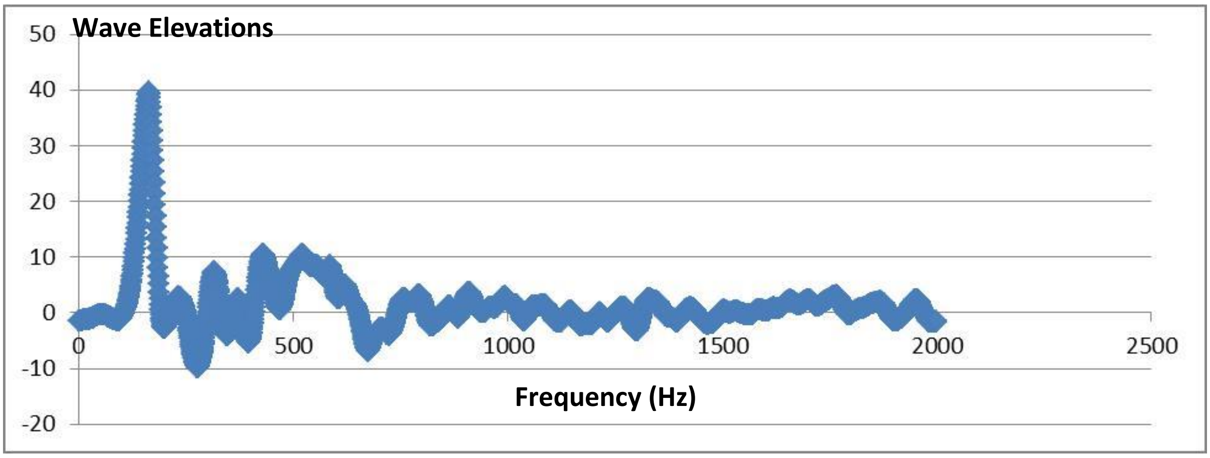
<u>Graph of wave profile frequency (Wave probe equipment)</u>

Model 1 (1st Run)

Channel 1 (20 seconds)

Maximum Elevation: 39.68 Wave Height: 49.48 mm

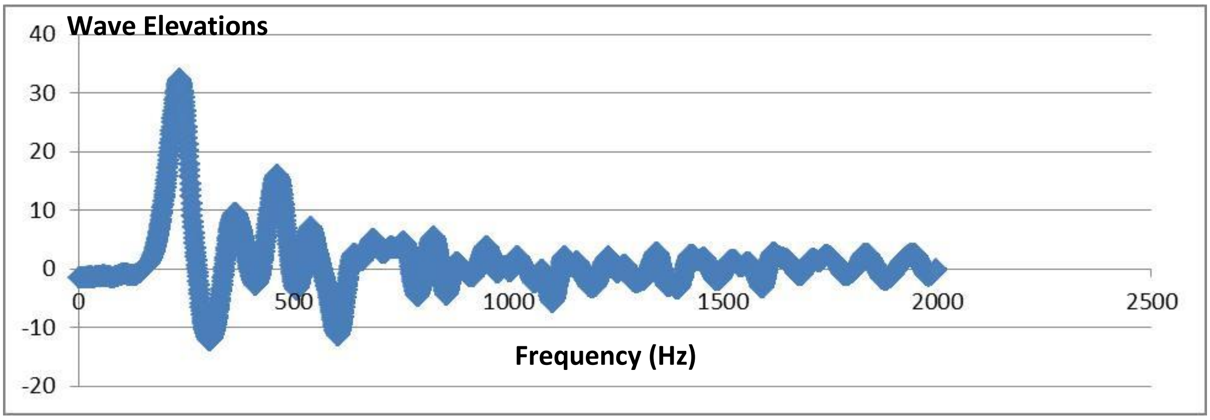
Minimum Elevation: -9.80



Channel 2 (20 seconds)

Maximum Elevation: 32.31 Wave Height: 44.68 mm

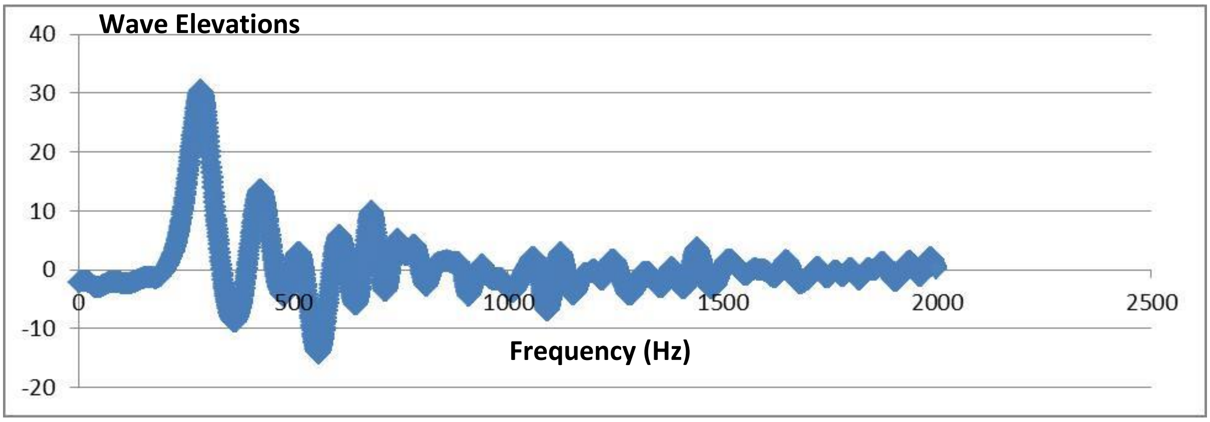
Minimum Elevation: -12.37



Channel 3 (20 seconds)

Maximum Elevation: 30.40 Wave Height: 44.63 mm

Minimum Elevation: -14.23

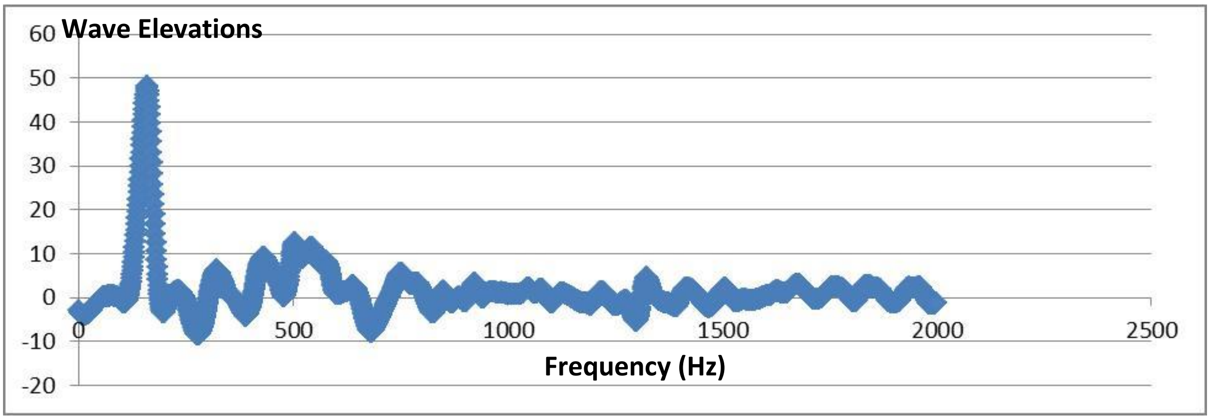


Model 1 (2^{nd} Run)

Channel 1 (20 seconds)

Maximum Elevation: 48.19 Wave Height: 56.81 mm

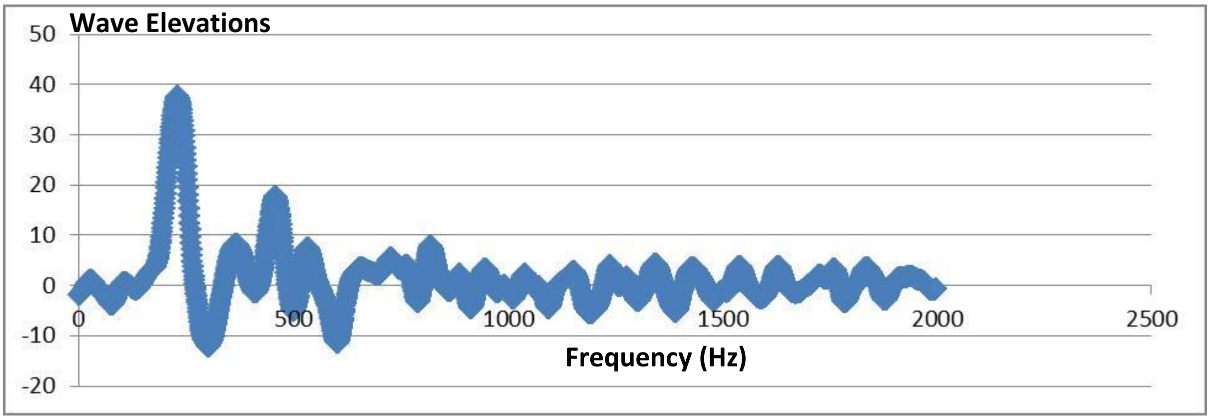
Minimum Elevation: -8.60



Channel 2 (20 seconds)

Maximum Elevation: 37.64 Wave Height: 49.99 mm

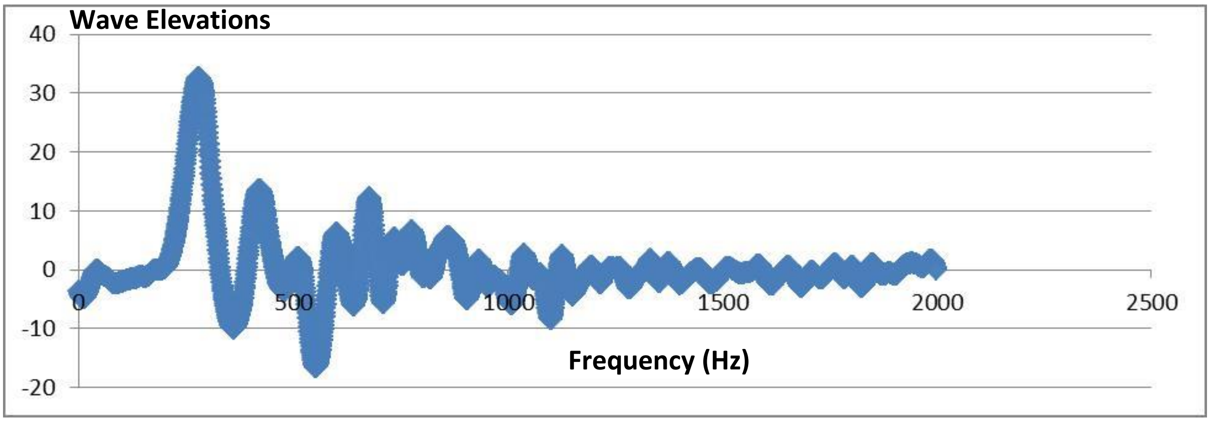
Minimum Elevation: -12.35



Channel 3 (20 seconds)

Maximum Elevation: 32.62 Wave Height: 49.25 mm

Minimum Elevation: -16.63

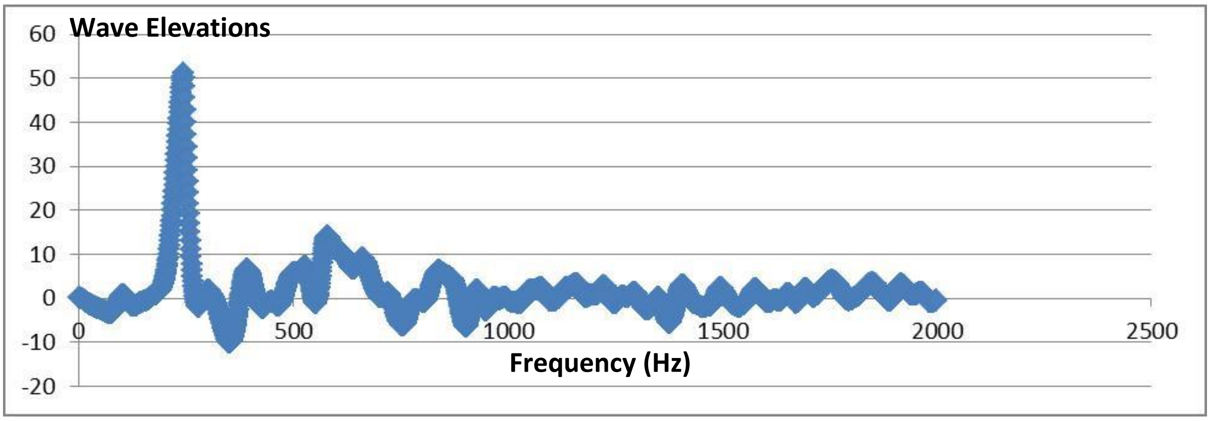


Model 1 (3rd Run)

Channel 1 (20 seconds)

Maximum Elevation: 51.16 Wave Height: 61.26 mm

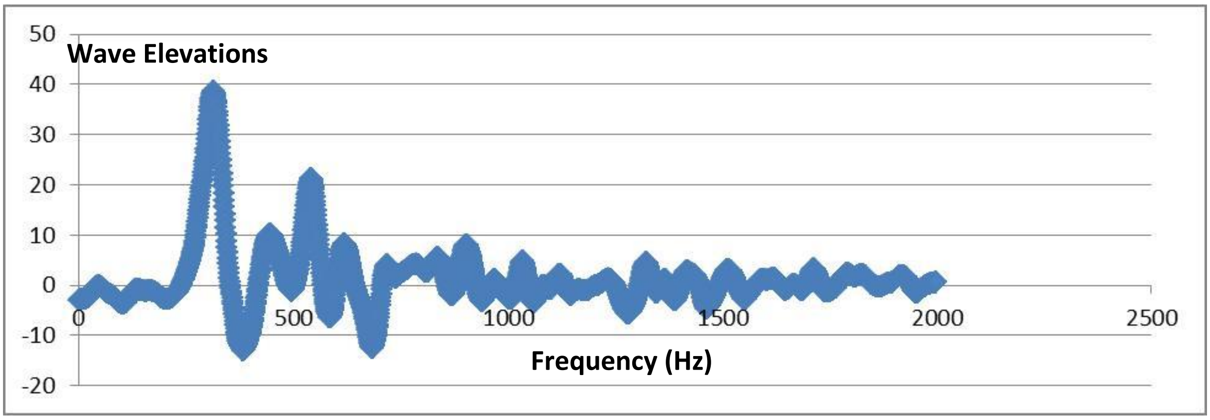
Minimum Elevation: -10.10



Channel 2 (20 seconds)

Maximum Elevation: 38.64 Wave Height: 51.64 mm

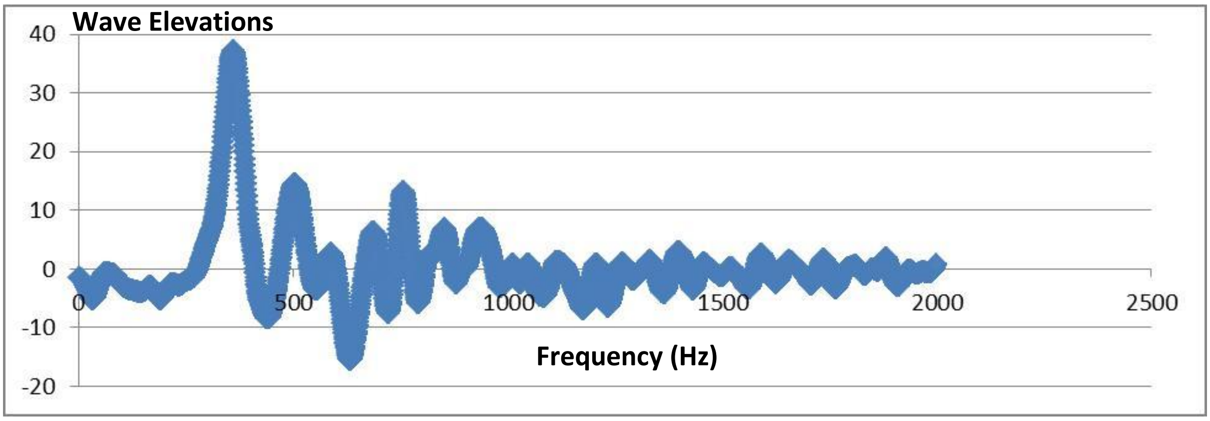
Minimum Elevation: -13.00



Channel 3 (20 seconds)

Maximum Elevation: 37.16 Wave Height: 52.84 mm

Minimum Elevation: -15.68

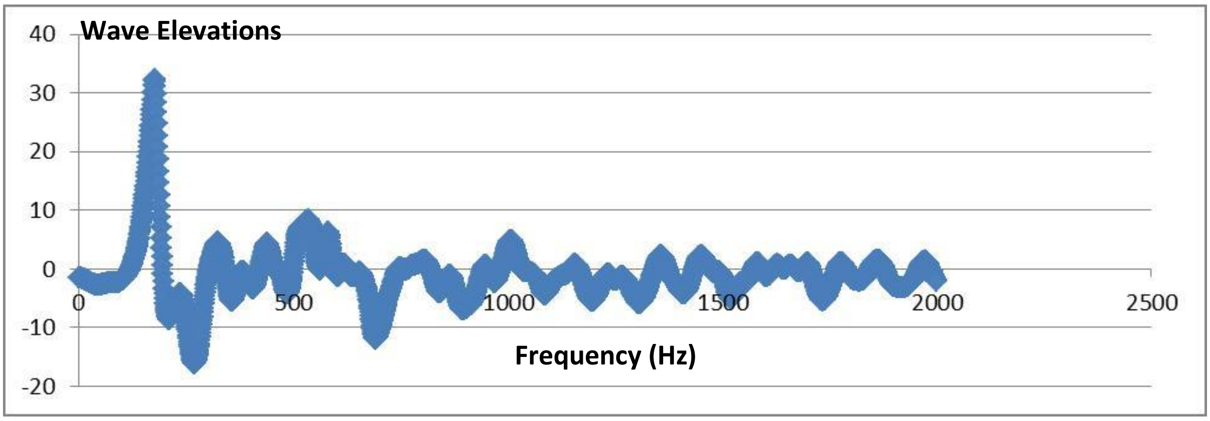


Model 2 (1st Run)

Channel 1 (20 seconds)

Maximum Elevation: 32.39 Wave Height: 48.56 mm

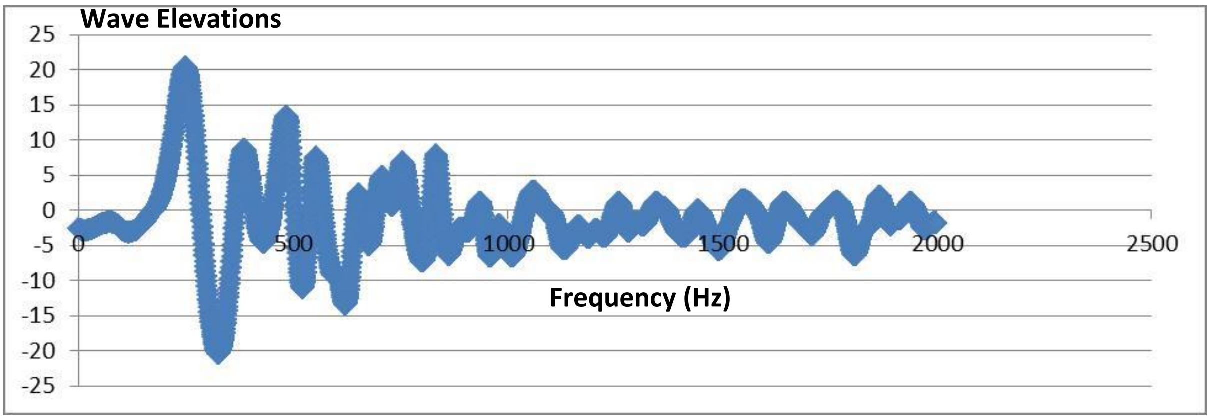
Minimum Elevation: -16.17



Channel 2 (20 seconds)

Maximum Elevation: 20.33 Wave Height: 40.82 mm

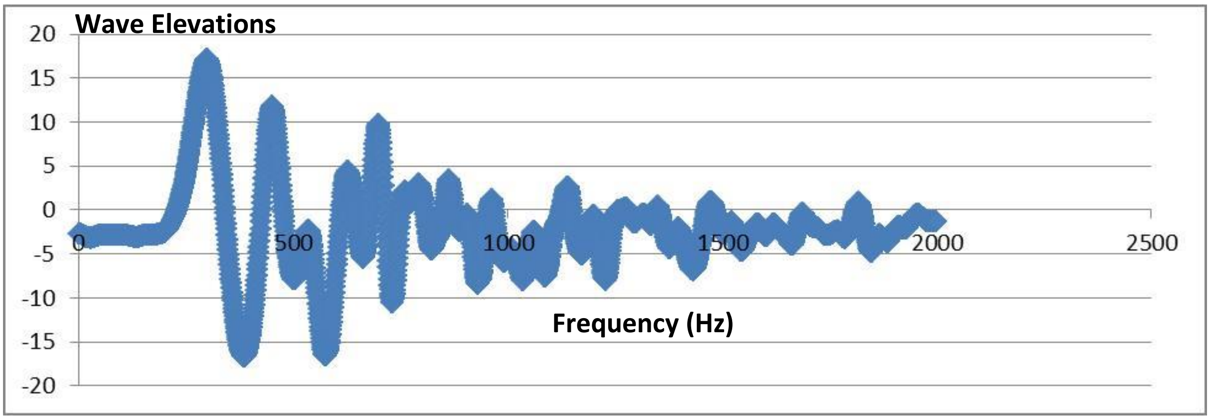
Minimum Elevation: -20.49



Channel 3 (20 seconds)

Maximum Elevation: 17.11 Wave Height: 33.89 mm

Minimum Elevation: -16.78

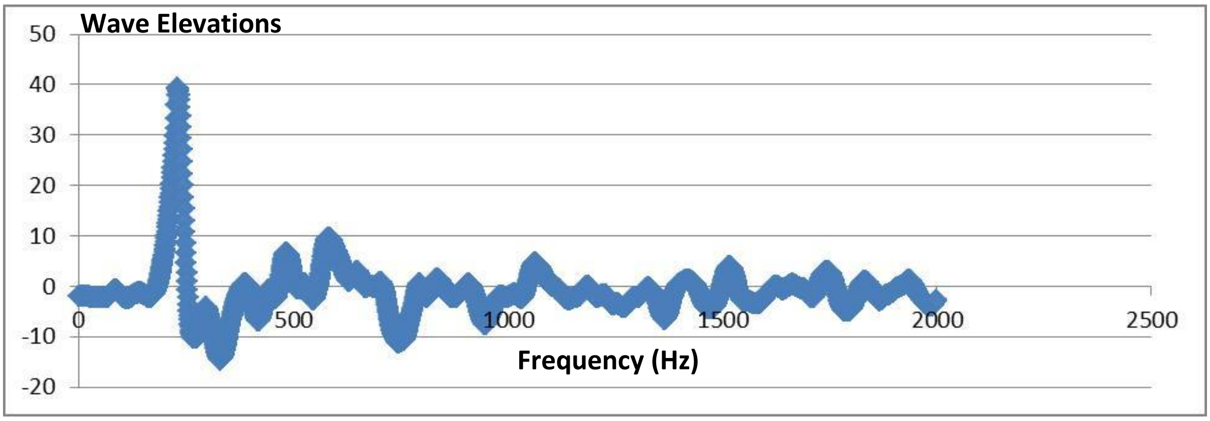


Model 2 (2nd Run)

Channel 1 (20 seconds)

Maximum Elevation: 39.46 Wave Height: 54.03 mm

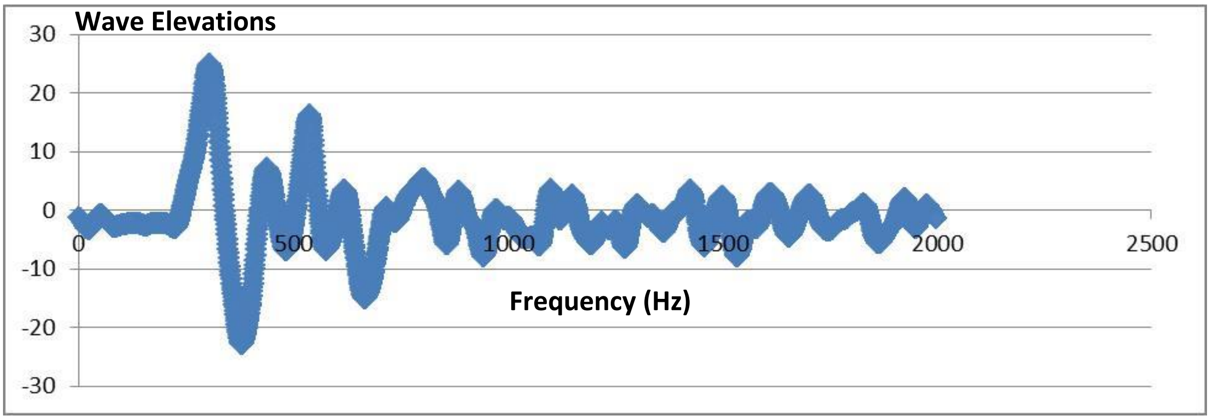
Minimum Elevation: -14.57



Channel 2 (20 seconds)

Maximum Elevation: 24.85 Wave Height: 47.77 mm

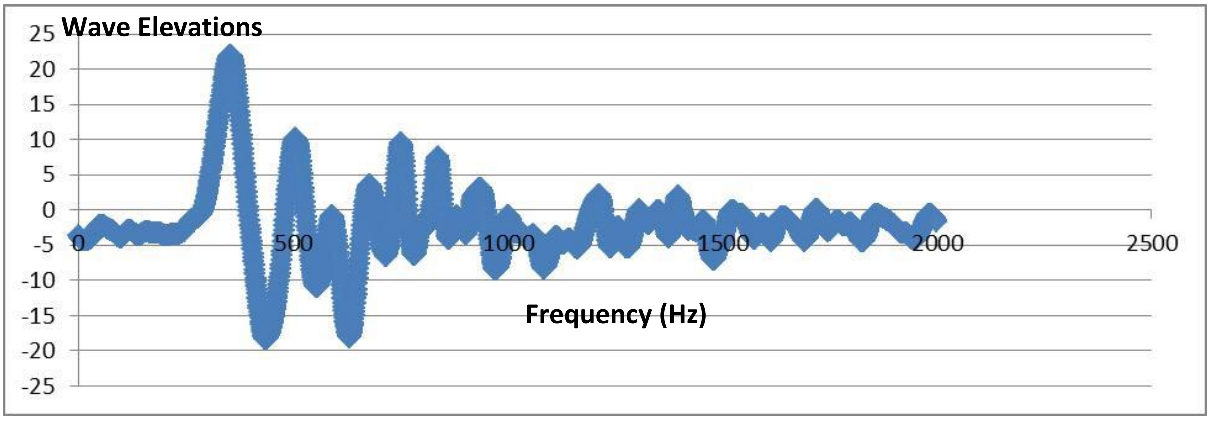
Minimum Elevation: -22.92



Channel 3 (20 seconds)

Maximum Elevation: 21.93 Wave Height: 40.34 mm

Minimum Elevation: -18.41

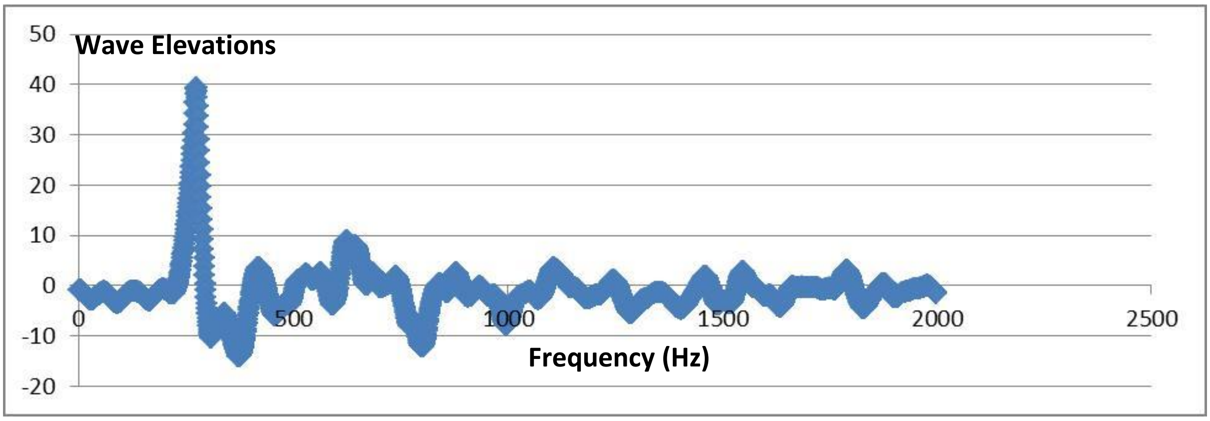


Model 2 (3rd Run)

Channel 1 (20 seconds)

Maximum Elevation: 39.39 Wave Height: 53.60 mm

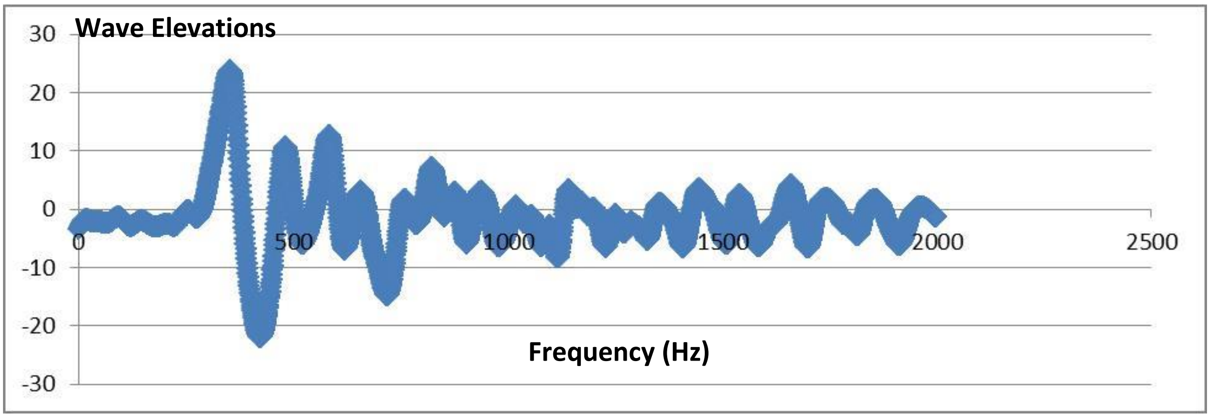
Minimum Elevation: -14.21



Channel 2 (20 seconds)

Maximum Elevation: 23.70 Wave Height: 45.67 mm

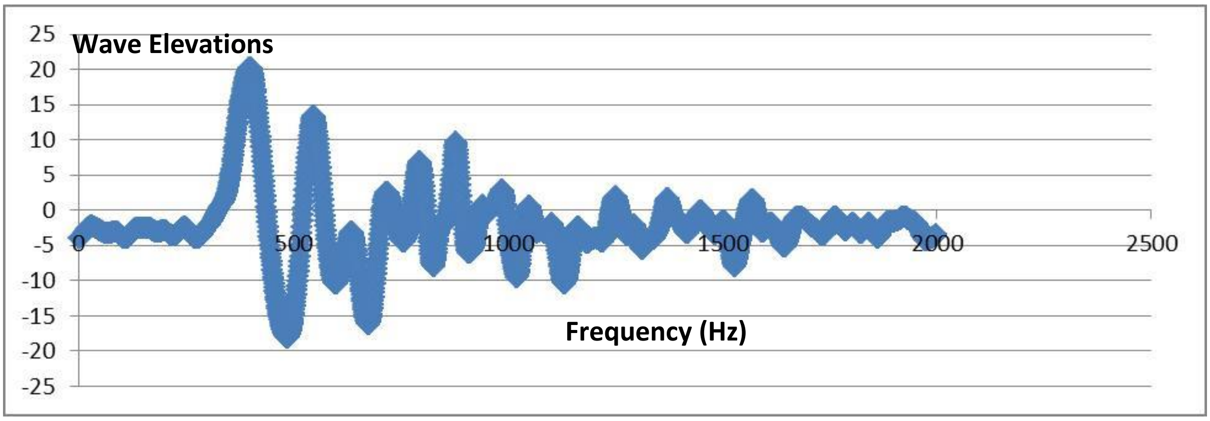
Minimum Elevation: -21.97



Channel 3 (20 seconds)

Maximum Elevation: 20.23 Wave Height: 38.35 mm

Minimum Elevation: -18.12

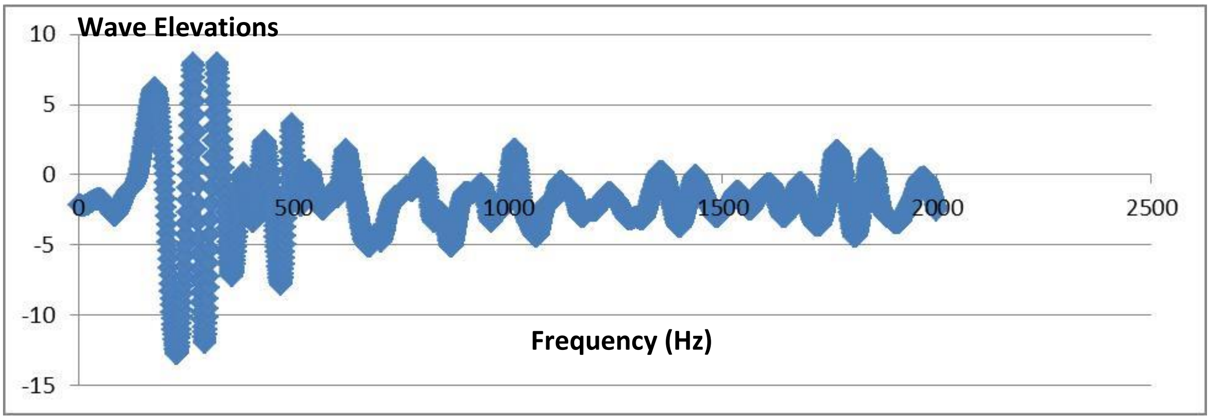


Model 3 (1st Run)

Channel 1 (20 seconds)

Maximum Elevation: 7.97 Wave Height: 20.79 mm

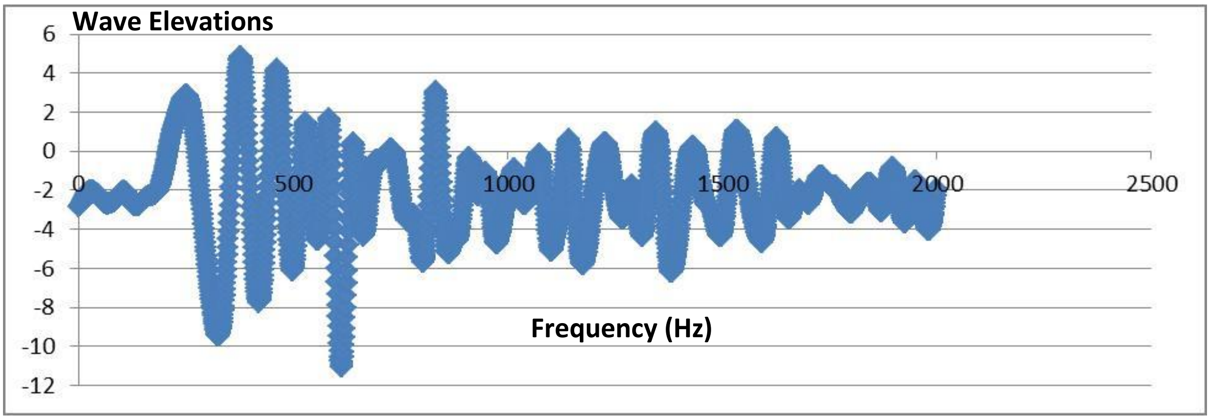
Minimum Elevation: -12.82



Channel 2 (20 seconds)

Maximum Elevation: 4.87 Wave Height: 15.94 mm

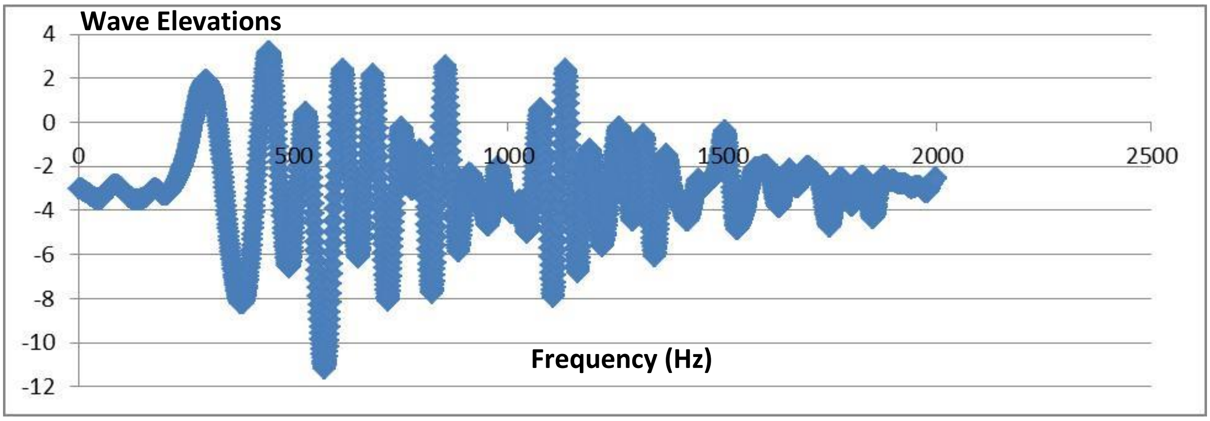
Minimum Elevation: -11.07



Channel 3 (20 seconds)

Maximum Elevation: 3.22 Wave Height: 14.40 mm

Minimum Elevation: -11.18

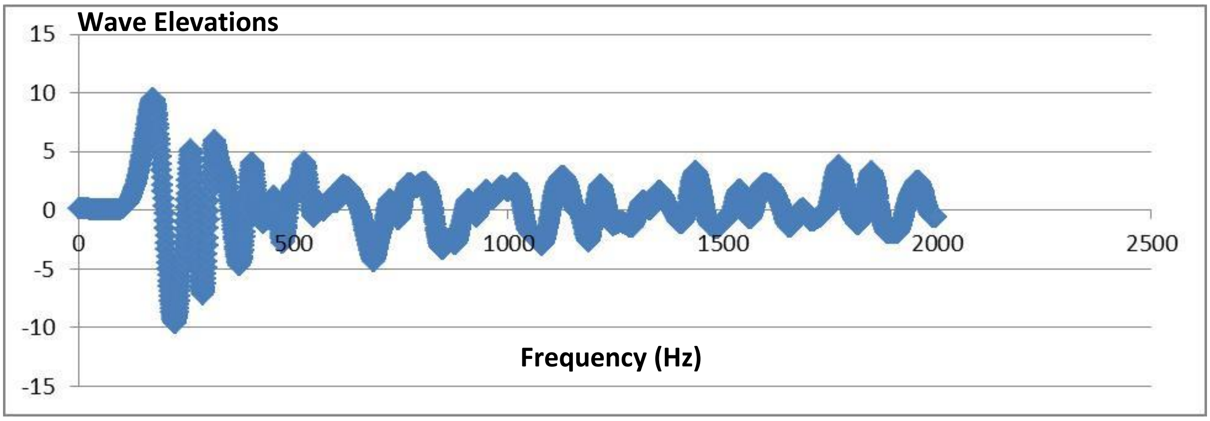


Model 3 (2^{nd} Run)

Channel 1 (20 seconds)

Maximum Elevation: 9.49 Wave Height: 19.11 mm

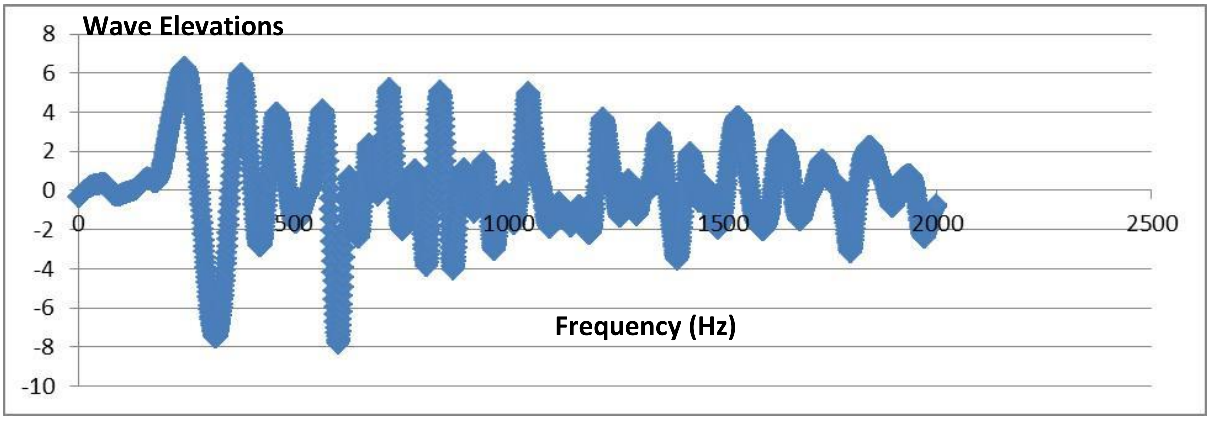
Minimum Elevation: -9.62



__Channel 2 (20 seconds)__

Maximum Elevation: 6.25 Wave Height: 14.12 mm

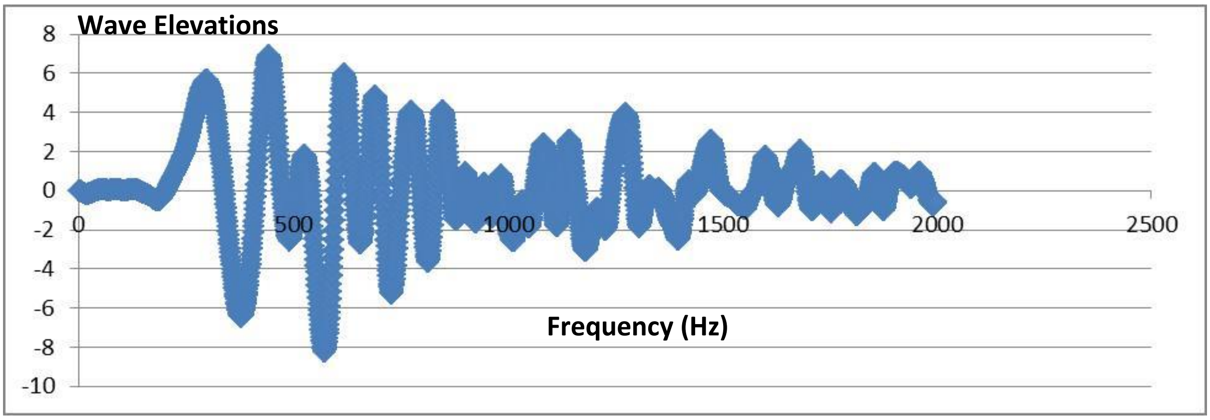
Minimum Elevation: -7.87



__Channel 3 (20 seconds)__

Maximum Elevation: 6.89 Wave Height: 15.14 mm

Minimum Elevation: -8.25

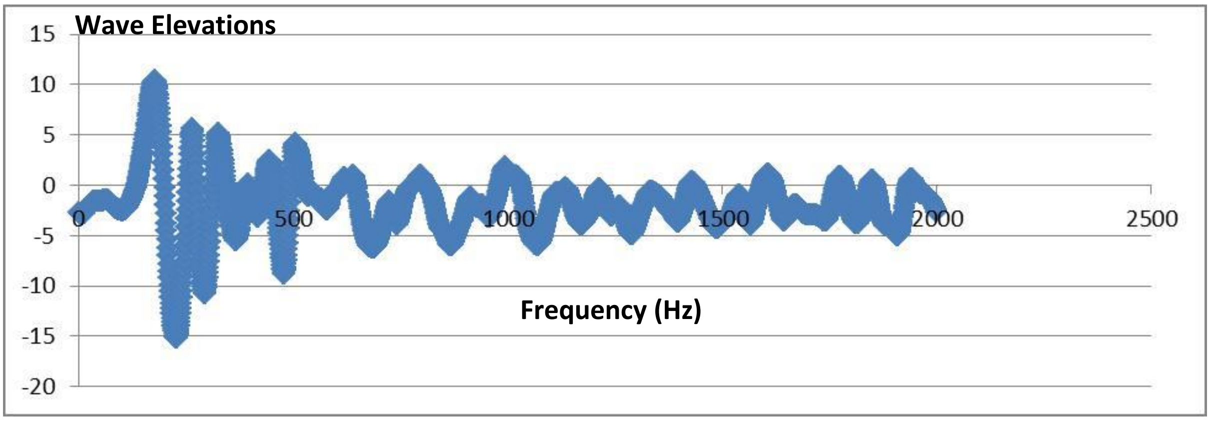


Model 3 (3^{rd} Run)

Channel 1 (20 seconds)

Maximum Elevation: 10.38 Wave Height: 25.61 mm

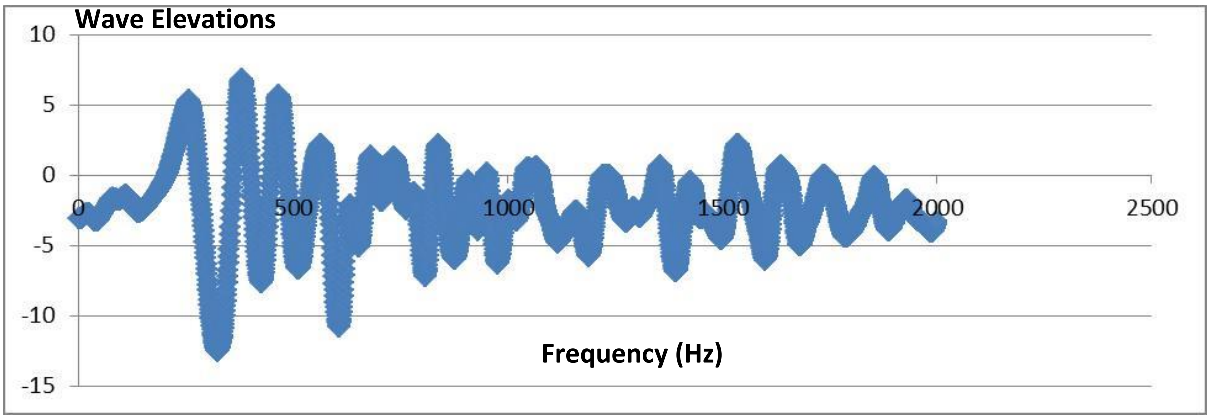
Minimum Elevation: -15.23



Channel 2 (20 seconds)

Maximum Elevation: 6.81 Wave Height: 19.38 mm

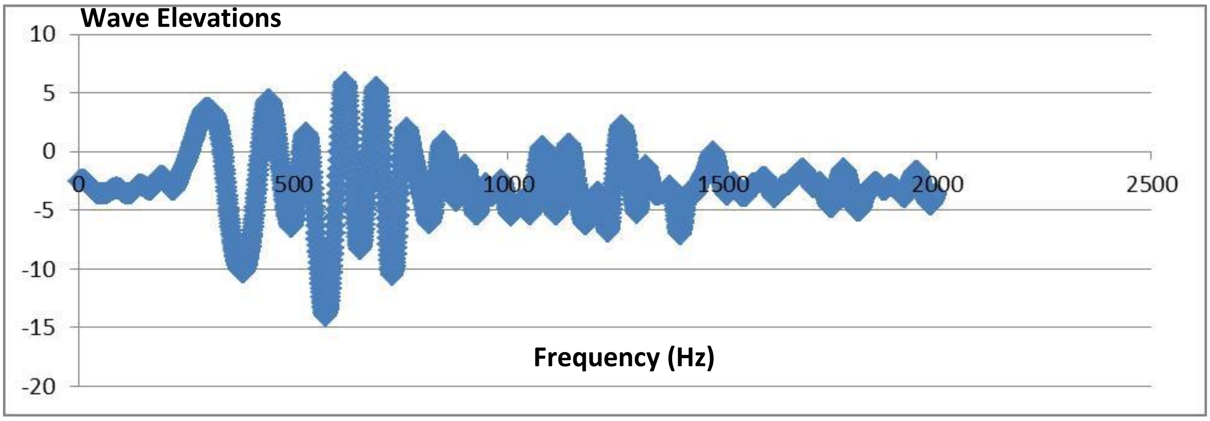
Minimum Elevation: -12.57



Channel 3 (20 seconds)

Maximum Elevation: 5.87 Wave Height: 19.90 mm

Minimum Elevation: -14.03



Tabulation of Data

Model	Channel	Average Wave Height (mm)
Model 1	1	55.85
	2	48.77
	3	48.91
Model 2	1	52.06
	2	44.75
	3	37.53
Model 3	1	21.84
	2	16.48
	3	16.48

Table of Average of Wave Height data