Hydrodynamic Test on IBS Block Work Structure

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Abstract. Industrialized Building System (IBS) is a method of construction which also refers to prefabrication technology. It is classified to a few categories based on the system used and block work system is one of the category in IBS. Block work system is a method of construction which uses blocks as the structural components with interlocking properties [1]. This system can become very efficient from the construction perspective, though the structural performance would differ from that of conventional. Therefore, this study explores more about the response of IBS block work buildings subjected to hydrodynamic load induced from hydrological disasters. The aim of this study is to measure the water pressure distribution along the surface of the IBS block work building and its displacement subjected to bore impact. It also covers the comparison between experimental results with results from computational analysis. In this study, there are a total of 4 models that was tested and analyzed. All of the models was scaled down to 1:5. Each model undergoes 3 testing which has different volume of water. The water pressure distribution was measured by pressure cells, while LVDT was used to measure top displacement of the structure. Results showed almost similar pattern for all models which have the maximum water pressure to be at the bottom part of the structure. Based on the response of the different models towards the bore impact, it showed that the presence of walls in the models affect the stiffness of the whole structure.

Introduction

Industrialized Building System (IBS) was first introduced in Malaysia in 1965. The introduction was initiated by the Ministry of Housing and Local Government. The objective was to obtain a quality constructed houses which is affordable and can be completed faster. From then on, the developments of IBS are progressing slowly with less system were introduced to the Construction Industry Development Board [1]. Construction industry in Malaysia is an important sector that contributes to the national Gross Domestic Product (GDP) for about 6 percent in the year 2015. The developing country such as Malaysia needs a variety of construction projects and its supply chain to benefit the other sector. Considering the construction industry as an important sector, IBS have a strong recommendation comparing to the conventional method of construction when it comes to a better results in terms of productivity, quality and also cost efficiency. Therefore, it gives better output to the other major sectors of economy in Malaysia.

Problem Statement

Buildings and structures are purposely constructed to provide shelter and protection for the users from any kind of exposures that might cause harm and difficulties. Natural disasters is one of the source of difficulties to humans, and some of the example is in terms of hydrological disasters such as flooding and tsunami. Flooding is an extreme phenomena which can be very destructive at massive scale. If water starts to invade to the places which is not designed to resist the pressure from the water and are submerged in a long period of time, it destroys and resulting to a great loss of facilities including buildings. Meanwhile, Tsunami is a large ocean wave due to displacement of massive volume of water that are caused by sudden motion on the ocean floor such as earthquakes. Occurrence like these often very catastrophic and may contribute to huge amount of loss and death, for instance the tsunami in Aceh, Indonesia on 26th December 2004. It was the most devastating natural disaster ever happened, with waves reaching 30 meters high, sweeping a total of 110,229 death and 4.4 billion dollar worth of damage [2].

Water in motion, can cause damages to properties, affecting most on buildings and infrastructures. This is because when water moves, it produce hydrodynamic loads, which exert a large magnitude of force onto the building. It often leads to a structural failure and thus diminishing the actual purpose of the buildings to act as a shelter for the occupant. It is hard to counter against this occurrence since it is caused by many environmental factors that are difficult to control. One of the alternative to act against this occurrence is to mitigate the building from damages. The alternative is to elevate the building by the use of stilts as the method of construction of the buildings. Stilts can be standardized as IBS-stilts and deployable on buildings.

IBS is still on the verge of being actively used in the construction sector due to its uncertainties of its outcomes. This is because there are limited information about the economy and capabilities of IBS. This have created a feeling of unconvinced towards IBS products, especially when it comes to the construction of buildings on area which is prone to hydrological natural disaster. Thus, a better knowledge of IBS is required in order to provide convincing solutions to the people through the usage of multi case of IBS as the method of construction in the future.

Objective

The objectives of the study are to measure the water pressure distribution along the surface of the IBS block work building and its displacements due to the water surge. Other than that, the aim of this study is to compare the result from experimental test between the IBS block work structure in the form of displacements to computational analysis.

Scope of Study

This study is focusing on pressure distribution of the hydrodynamic loads acted to an IBS block work structure. The scope for this study consist of:

1. Conducting a hydrodynamic test onto 7 models of which consist of 2-Storey IBS block work structure including Full Structure (all side for both floor have walls), Unsymmetrical (front and right wall on first floor removed), Symmetrical (all side on first floor have no walls), Frames Only (all side for both floor have no walls), 1-Storey Frames with slab, 1-Storey Frames without Slab and columns only for both 1-Storey and 2-Storey height.
2. Comparing the results obtained from the experimental testing in between the first four model of IBS block work structure models tested.
3. Comparing in between the results from the experimental testing for the first four model and the result from computational analysis.

Literature Review

Block Work System

Blocks work system exists as one of the type of IBS because of the revolutionary of construction method of using conventional bricks with the usage of interlocking concrete masonry units (CMU) and lightweight concrete blocks. The blocks are commonly produced by hydraulic machinery which presses them in the steel molds with the presence of vibration to compact the blocks. The present trend is directed toward an interlocking reinforced building block which includes steel rods as the reinforcing elements embedded inside the block and with the use of steel plate, bolts and nuts placed on the top of the blocks to make the blocks fixed in position [3].

Hydrodynamic Loads

Hydrodynamic load is the frontal impact loads from the upstream flow which is created from the rapid flowing of water towards the building [4]. Other than frontal impact loads, hydrodynamic load also creates drag on the sides of the building and suction on the rear face of the building. The magnitude of the hydrodynamic loads is dependent upon the velocity of the floodwaters and the shape of the structure. Hydrodynamic loads includes the drag/velocity-dominated (quasi-static, F_{qs+}) loads and the inertia/acceleration-dominated (impulsive, F_{max}) loads [5].

Frame Analysis

The concept used in the software Multiframe involved the use of matrix stiffness method to solve a system of simultaneous equations to determine the forces and deflections in a structure [6].Each member are connected and replaced with line elements in which its stiffness have already been defined based on the geometrical cross section of the member. It perform a first order linear elastic analysis which the structures are assumed to behave linearly elastic, assuming that there is a linear relationship in between the force acted onto the structure and its displacement due to the relative force.

Methodology

The method used to achieve the objectives are divided into four stages of work. The stages are consisting of preliminary stage, experimental testing, numerical modeling, result and analysis of data to reach the aimed conclusion and recommendations. Figure 1 shows flow of the stages of research work.

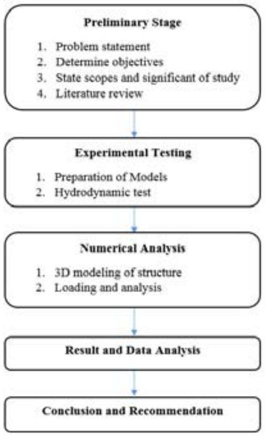


Figure 1: Flow of research work

Experimental Testing

There are a total of 7 models of IBS block work structures were tested in the experiment. Only the result from the first 4 models was discussed in the analysis of this study. All of the models are scaled down to 1:5 from the real structure according to Similitude Rule. Each model have the same main structural dimension. The length, width, and total height of the structure is 740mm, 740mm, and 3200mm respectively. The first floor and the second floor having a height of 740mm and 640mm respectively with the total height of the 2-storey structure is 1380mm. The first 4 models which consist of full structure, unsymmetrical structure, symmetrical structure and frame structure, are 2-storey in height. Meanwhile, the other 2 models which is frames with slab and frames without slab are 1-storey high. For the last model, it consist of two single column with 1-storey and 2-storey height respectively. Figure 2 shows the view of four models that are focused on in this study.

For each of the model, they were tested 3 times which consist of a testing with different impounding water depth of 1.0m, 1.5m and 2.0m from the same direction of flow (frontal flow). Each of the impounding water depth holds a total of 3.67 m^3, 6.15 m^3, and 8.42m^3 volume of water in the tank respectively. The impounding water depth is manipulated for the testing of each model to create different volume of water being released onto the structure, thus exposing each of the model with different water pressure. Figure 3 shows the dam break initiator tank used in the experimental test and the annotation coordination of the structure to assist in the analysis.

Figure 2: View of models (from the left), full structure, unsymmetrical, symmetrical, and frames.

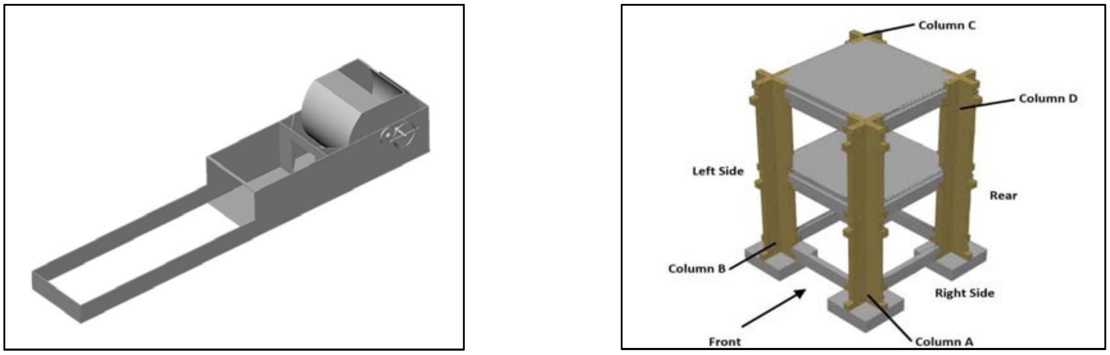


Figure 3: Dam Break Initiator Tank (left) and Annotation coordination of the structure (right)

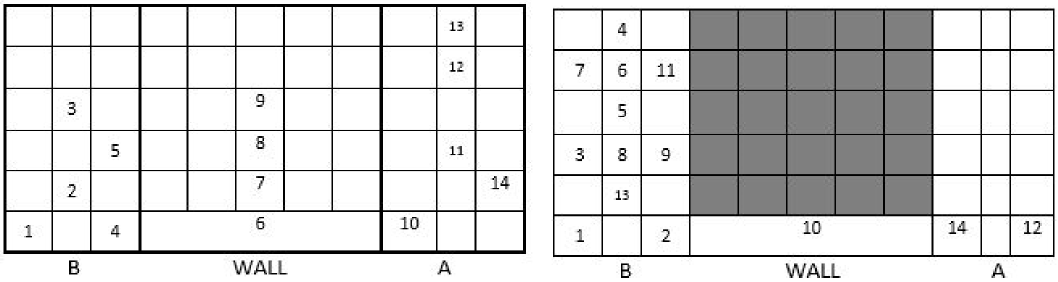


Figure 4: Location of pressure cells for full structure (left) and the other three models (right)

The result of pressure reading from pressure cell and displacement reading from LVDT was collected from data logger for each of the testing. Figure 4 shows the location of pressure cell while Figure 5 shows the position of LVDT (50mm) used in the testing.

Figure 5: Position of LVDT (50mm) used in the testing

Numerical Stiffness Frame Analysis

Multiframe4D was the software used to analyze each of the model of IBS block work structure with respect to the experimental test done in this study. All of the members of the structure are simplified into line elements. These line elements represent the centroid of the members, which are manually constructed by using the dimensions just as the real structure was. Each of the line was defined for specific section properties based on its type of member components. The joint in which it is considered connected to a footing were defined as a restrained known as fixed support. The procedure of using this software involves two main activities which is preparing the 3D model of the structure, which are shown in Figure 6, and the second one is to state and define the loading acted onto the structure, before it can be analyzed.

Loading was assigned onto the structure based on the data from the pressure cell in the experimental testing which was converted into force distribution per meter width. For all of the models, the load combinations used are the same which consist of the force distribution from the water surge and the self-weight of the structure. The output from this analysis was the top displacement of the structure.

The materials used in each of the section properties has the properties such as shown in Table 1. Since the all of the component of the structure was ready-made, the material properties was obtained from the previous study based on the testing carried out when it was casted [7].

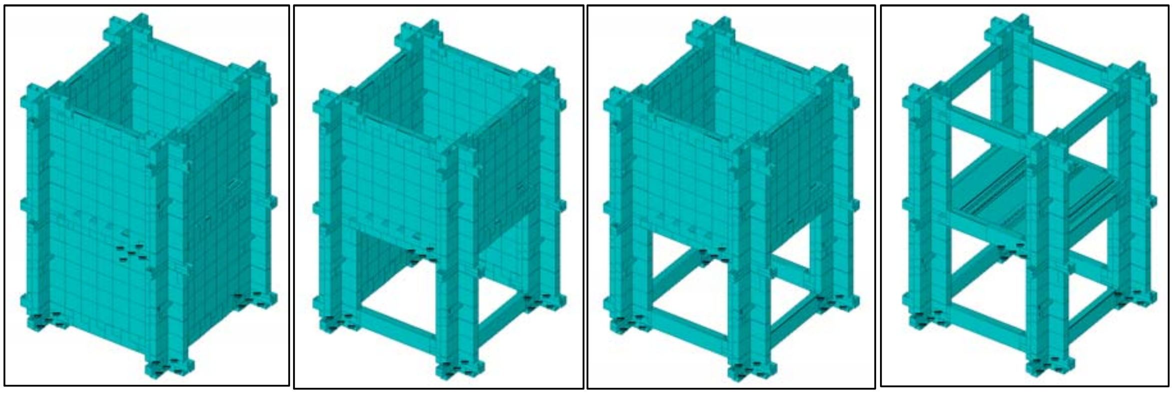


Figure 6: View of rendered 3D models (from the left), Full Structure, Unsymmetrical, Symmetrical, and Frames model.

Table 1: Material properties

Material	Density (kg/m^3)	Yield Stress (MPa)	Modullus of Elasticity, E_c (MPa)
Concrete	2500	30	20000
Steel	7865	250	200000

Result and Discussion

Bore Induced Pressure on IBS Models

Based on the result from the experimental test, the pressure-time history for each of the pressure cell was obtained. Figure 7 shows the pattern of pressure time history of 1.0 m, 1.5 m, and 2.0 m impounding water depth for full structure model. The other 3 models have about the same pattern as shown in Figure 8 but with different maximum pressure and duration of the structure subjected to water pressure.

The average maximum pressure exerted to the structure was 8 kN/m^2, 16 kN/m^2, and 20 kN/m^2 for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively. The highest pressure was located around the middle beam and the inner side of the columns and the pressure decreases as the location of the pressure meter go higher. The highest pressure was exerted on the first 0.2 m height of the structure. For all of the models, the maximum pressure happened on the 4th second, and the fluctuation of pressure happened in a range of 6-15 seconds just after the peak pressure was achieved before it and the flow eventually stabilized and decreases gradually

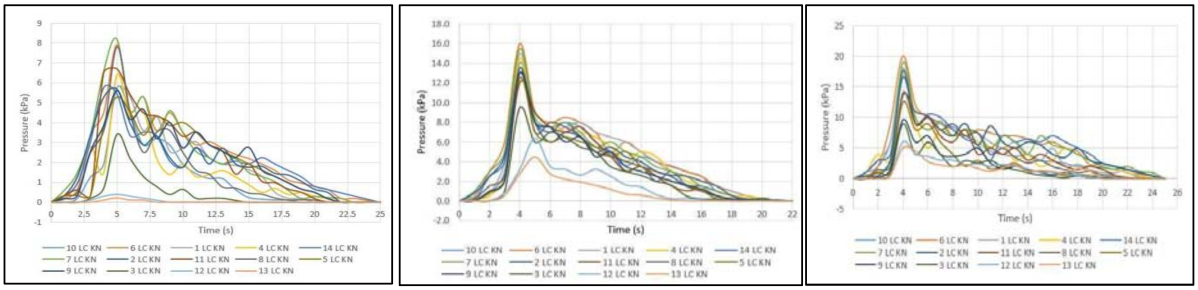


Figure 7: Pressure-time history of full structure model for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively (from the left)

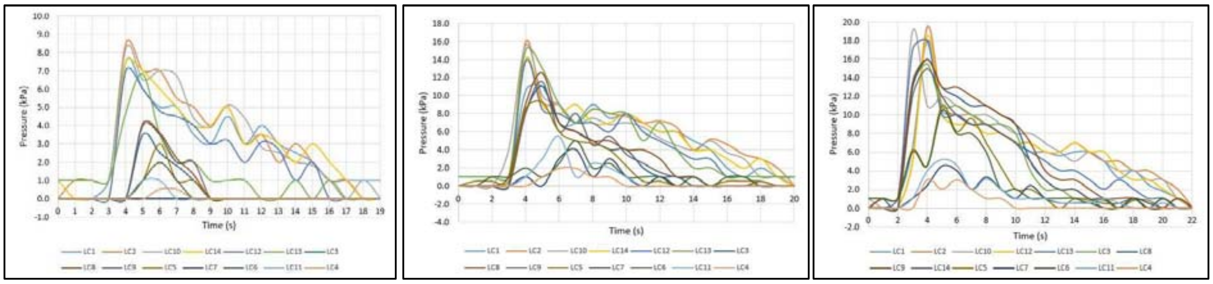


Figure 8: Pressure-time history of symmetrical structure model for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively (from the left)

Based on Figure 8 (1.0 m impounding water depth), there was near to zero pressure recorded by pressure cell 13 and 12. This is because both of the pressure cell was located higher which the bore pressure does not reach, as shown in Figure 9 (left). For Figure 9 (right), the photo was taken during the bore impact for 2.0 m impounding water depth, which explained why pressure cell 10 received the highest pressure in Figure 8 because it is located in the middle where the water surge pressure are focused.

Figure 9: Photo showing pressure cell 12 and 13 on full structure model was higher than the maximum bore impact (left), and the pressure focused on the middle part of the structure during maximum bore impact on symmetrical structure model (right).

Estimated Maximum Force Distribution

From the pressure-time history, the maximum pressure was taken on each subdivided height of the structure. The maximum pressure was converted into maximum distributed force that are assumed to be uniform along the width of the structure. Figure 10 shows the division of area on the structure from front view. The width of the column are consider to be 0.24 m while the width of the wall is 0.5 m. The height are subdivided into sections of 0.1 m along the height of the structure.

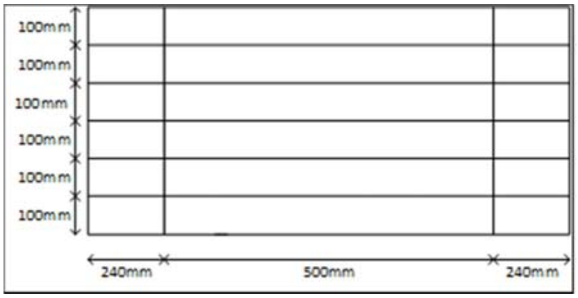


Figure 10: Subdivision area of structure from the front view for pressure identification.

The calculation of area exposed to bore impact is different for full structure and the other three structure. Full structure model have larger total area compare to the other three models because of the presence of wall. Table 2 shows the calculation of area based on models. The example of calculation for both maximum force distribution and the total maximum force acted on the structure are shown in Table 3.

Table 2: Calculation of area per 0.1 m height based on models

Model	Calculation	Total area per 0.1 m height (m^2)
Full Structure	(2 x 0.24 m) + 0.500 m	0.098
Unsymmetrical, Symmetrical and Frames only	0.24 m + 0.24 m	0.048

Table 3: Calculation for maximum force distribution and total maximum force for 2.0 m of impounding water depth on full structure model

Height (m)	Area (m^2)	Max. pressure (kN/m^2)	Max. Force Dist. (kN/m)	Total Max.Force per height (kN)
0.1	0.098	20.0	2.00	1.96
0.2	0.098	19.0	1.90	1.86
0.3	0.098	14.0	1.40	1.37
0.4	0.098	9.6	0.96	0.94
0.5	0.098	6.0	0.60	0.59
0.6	0.098	5.0	0.50	0.49
			Total Max. Force =	**7.21**

The results from all of the testing showed almost similar pattern of maximum distributed force. Figure 11 shows the maximum force distribution of 1.0 m, 1.5 m, and 2.0 m impounding water depth for full structure model. The other 3 models have about the same pattern as shown in Figure 12 but with different maximum force distribution. The total maximum force that acted onto structure for all model is shown in Figure 13.

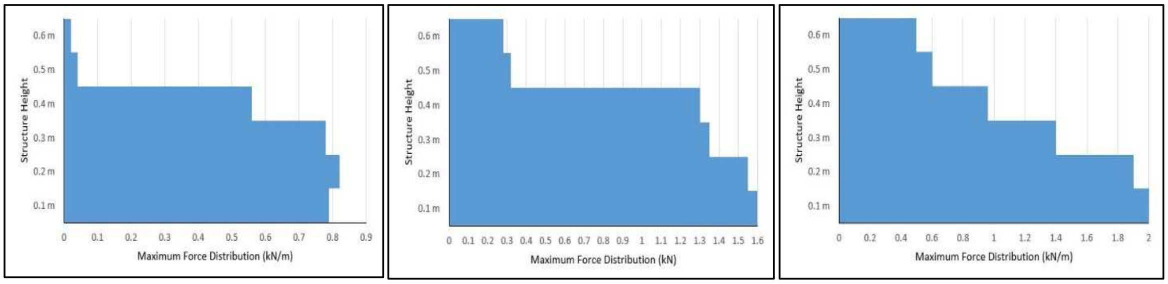


Figure 11: Maximum force distribution of full structure model for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively (from the left)

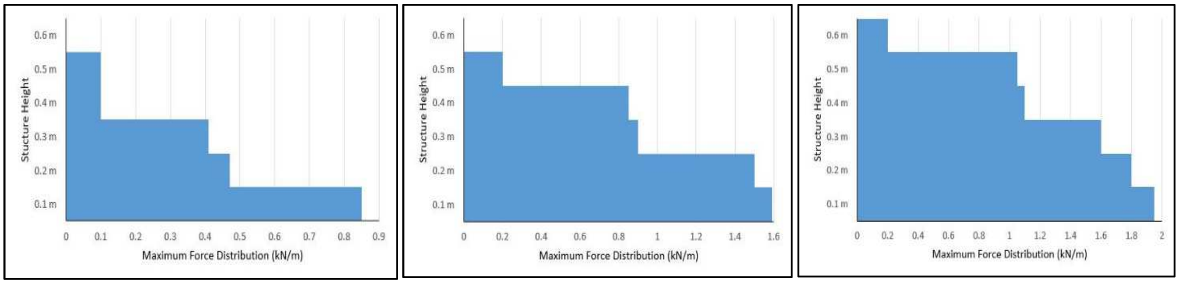
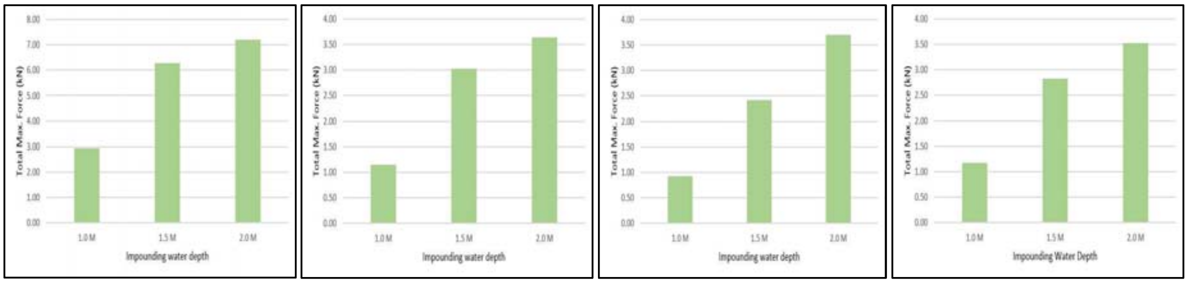


Figure 12: Maximum force distribution of symmetrical structure model for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively (from the left)



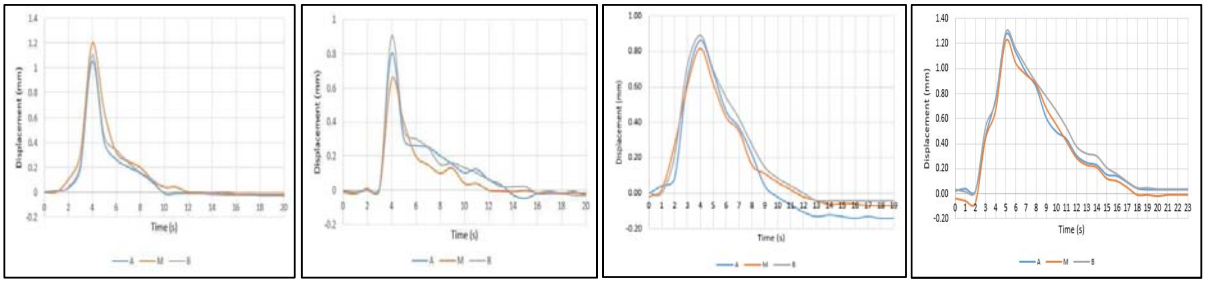
(a) (b) (c) (d)

Figure 13: Total maximum force acted to the structure for (a) Full structure, (b) Unsymmetrical, (c) Symmetrical, and (d) Frames model

Response of IBS Model Subjected to Bore Impact

The top displacement of the structure was also obtained based on the reading from LVDT installed at the top of the structure. Figure 14 shows the pattern of displacement of the full structure model due to 1.0 m, 1.5 m, and 2.0 m impounding water depth. The pattern is about the same for the other 3 models but vary in terms of maximum displacement.

The maximum displacement of the structure subjected to the maximum pressure was 1.20 mm for full structure, 0.85 mm for unsymmetrical structure, 0.95 mm for symmetrical structure and 1.30 mm for frames only structure



(a) (b) (c) (d)

Figure 14: Displacement vs time of (a) Full structure, (b) Unsymmetrical, (c) Symmetrical, and (d) Frames model, for 2.0 m impounding water depth

Computational Frame Analysis Result

The type of load being as the input in the computational analysis was uniform distributed load and the magnitude for the load was taken from the maximum force distribution. Generally, the deformation of the models are as shown in Figure 15. The result of the computational analysis is shown in Figure 16 which is in terms of displacement.

The result shows that all of the models have the highest displacement on the columns. Between all of the models, the highest maximum displacement was 1.32 mm which is for frame model subjected to 2.0 m impounding water depth, while the lowest maximum displacement subjected to the same impounding water depth was unsymmetrical model which have the value of 0.72 mm.

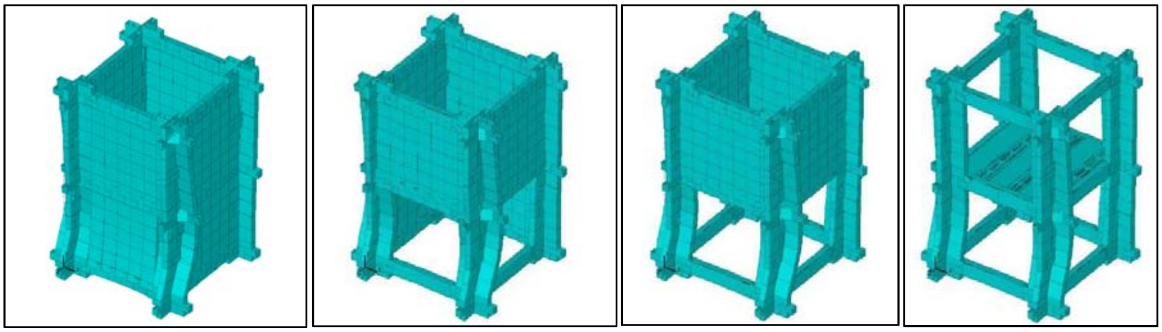
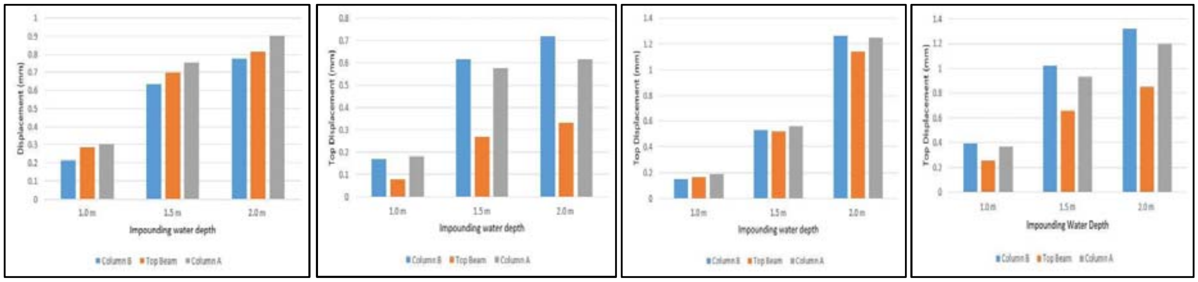


Figure 15: Deformation of models due to maximum force distribution for 2.0 m impounding water depth (from the left, full structure, unsymmetrical, symmetrical, and frames model)

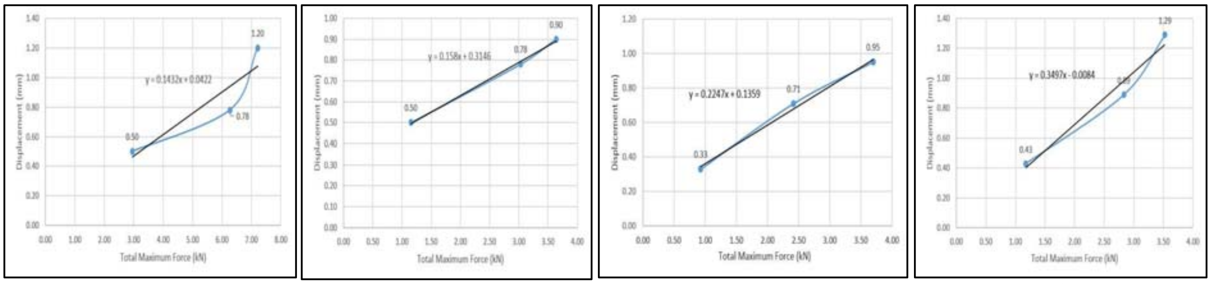


(a) (b) (c) (d)

Figure 16: Top displacement of (a) Full structure, (b) Unsymmetrical, (c) Symmetrical, and (d) Frames model, for every impounding water depth

Comparison of Response of Structure between Experimental Results

Based on the results from experimental testing, a graph of maximum displacement versus maximum force acted onto the structure was drawn for each of the models. Each of the graph were included with trend line (the black line) including the linear equation of the line. The equation shows the stiffness relation between the force acted onto the structure and the response of the structure in the form of displacement due to the force acted onto it. Figure 17 shows the graph of total maximum force acted onto the structure versus the maximum displacement for the models.



(a) (b) (c) (d)

Figure 17: Graph of maximum force acted onto the structure versus the maximum displacement for (a) Full structure, (b) Unsymmetrical, (c) Symmetrical, and (d) Frames model

The equation form each of the trend line was taken as the main source of comparison in between the models for the experimental results. The equation are representing the stiffness of the structure, therefore the comparison are done by introducing the same value of force, which is consider to be the 'x' in the trend line equation, to get the displacement ('y' value from the trend line equation) of the structure due to the introduced force. Table 4 shows the displacement of the structure based on the equation of the trend line after introducing 5 kN of force into the equation.

Table 4: Displacement value due to the force introduced in the trend line equation

Model	**Trend Line Equation**	**Force (x), kN**	**Displacement (y), mm**
Full structure	$y = 0.14319x + 0.04222$	5.0	0.76
Unsymmetrical Structure	$y = 0.158x + 0.3146$	5.0	1.11
Symmetrical Structure	$y = 0.22472x + 0.13588$	5.0	1.26
Frames Only Structure	$y = 0.3497x + 0.0084$	5.0	1.74

Based on Table 4, the result shows that the wall contributes critically in the stiffness of the structure. This can be proved by comparing the displacement of full structure and unsymmetrical structure, where the unsymmetrical structure have about 46 percent higher displacement than the displacement for full structure. This shows that the wall acts as a stiffener to the frame that is parallel to the direction of the force which is also called as the Moment Resisting Frame. The wall also can be considered as the secondary structural member that can distribute the external load internally throughout the whole structural members.

The result of removing another wall from unsymmetrical to become symmetrical structure have less effect towards the stiffness of the structure since the increase in displacement is only about 14 percent. This shows that installing unsymmetrical wall is not efficient when it comes to increasing the stiffness of the structure since it only decreases the displacement by 30 percent. Even though the removal of front wall reduce the maximum force acted onto the structure to about 53 percent (shown in Figure 18), the structure stiffness was reduced, resulting to an increase of displacement when the structure is acted with external force.

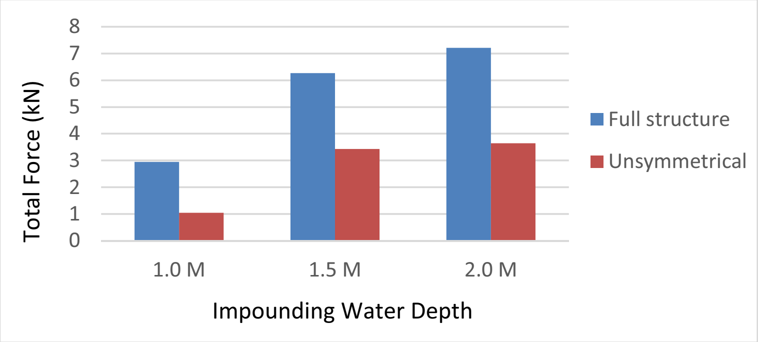
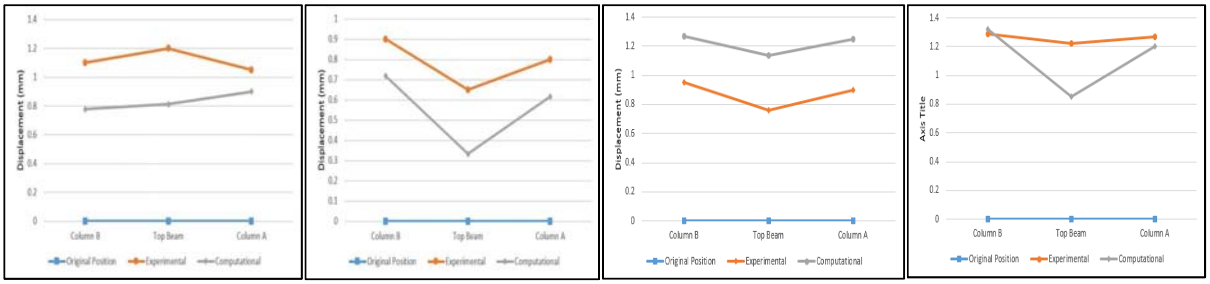


Figure 18: The reduction of total force acted on structure for models with front wall (full structure) and without front wall (unsymmetrical)

By comparing the displacement of full structure and frames only structure, there is an increase of displacement of about 130 percent. One of the possibility that contribute to the major change in stiffness of structure is that the weight of the structure is reduced after the all of the walls were removed. IBS block work system is a structure that depend on the interlocking features in between the blocks as one of the main contributor to the stability and stiffness of the structure. Weight of the structure is one of the component that contribute to the interlocking features of the block. Therefore when the wall is removed, the weight of the structure decreases, thus the interlocking in between the blocks decreases, resulting to a less stiff structure and increased displacement when exerted with external force.

Comparison for Response of Structure between Experimental and Computational Results

The comparison between the results of experimental testing and computational analysis was done by focusing on the displacement of the structure for each model for 2.0 m impounding depth only since these are considered to be the most critical among the other impounding water depths. The displacement of both results were combined into one graph which is shown in Figure 18 as the top displacements of the models from plan view.



(a) (b) (c) (d)

Figure 19: Top displacement of (a) Full structure, (b) Unsymmetrical, (c) Symmetrical, and (d) Frames model from plan view

Figure 19 (a) shows that the displacement for experimental testing was higher than the computational analysis by an average 35 percent. The highest displacement for experimental was on the top beam while for the computational analysis was on column A. There are difference in terms of location for the maximum displacement because the pressure are highest on the middle beam for the experimental, while for the computational analysis, the force were assumed to be uniform along the width of the structure.

For Figure 19 (b), the displacement of the structure in experimental testing was about 28 percent higher than the result from computational analysis. Both of the results show the same pattern of structure displacement, which have the highest displacement on both of the columns, while minimum on the beam. Both shows that the highest deflection are on column B, in which there are wall attached to. This means that the wall on that side of moment resisting frame is not functional as a stiffener as it does not decrease the deflection of column B.

Referring to Figure 19 (c), the result was different to the other models. The displacement from the computational analysis was 40 percent higher than the displacement from experimental testing although they share the same pattern for structure displacement with Figure 19 (b). One of the reason that the displacement for computational is higher than experimental is the actual load exerted to the structure is different. The displacement for computational analysis is based on the maximum uniform force distribution acted to the structure while the displacement from experimental was due to the load from bore impact, which is not uniformly distributed along the width of the structure, since the water surge behavior is very erratic and fluctuating. Thus, for the experimental testing, the average actual pressure was taken for each subdivided height, and then multiplied with the area of the structure, in order to get the actual total force acted onto the structure Table 5 shows that the actual total force that acted onto the structure in the experimental testing was 23 percent smaller than the total force exerted onto the structure in computational analysis. Therefore, the displacement is lower for experimental result since the total force acted was lower.

Table 5: The total maximum force acted onto the structure based on average actual pressure.

Case	**Average Actual Pressure for each height (KN/m^2)**						**Area (m^2)**	**Total Max Force (kN)**
	0.1 m	0.2 m	0.3 m	0.4 m	0.5 m	0.6 m		
Experimental	17	15.5	15.7	4.6	3.63	3	0.048	2.85
Computational	19.5	18	16	11	10.5	2	0.048	3.70

Figure 19 (d) shows that the displacement of columns for both result are almost the same with having only about 5 percent differences, but for the displacement of beam, the result from experimental testing was 43 percent higher than the displacement in computational result. This shows that the beam in experimental testing was fully affected to the response of the columns towards the load exerted to the structure, while in the computational analysis, the beam is partially affected to the response of the columns.

Conclusion

Based on the objective of this study, it can be concluded as follow:

1. The pressure distribution along the surface of the structure was obtained and the average maximum pressure exerted to the structure was 8 kN/m^2, 16 kN/m^2, and 20 kN/m^2 for 1.0 m, 1.5 m, and 2.0 m impounding water depth respectively. The area which was affected with the highest pressure was located around the middle beam and the inner side of the columns. The pressure decreases as the height of the column increases, and the highest pressure was exerted on the first 0.2 m height of the structure. . In general, the maximum pressure happened on the 4th second, and the fluctuation of pressure happened in a range of 6-15 seconds just after the peak pressure was achieved before it, and the flow eventually stabilized and decreases gradually.
2. The wall component contribute to the stiffness of the structure which was proved based on the displacement of full structure having the least value compare to the other models, having a difference of 46% for unsymmetrical, 66% for symmetrical and 130 % for frames only structure.
3. The result in between experimental testing and computational analysis based on the displacement of the structure was having differences in a range of 28 – 43 percent.

As for future research of topics related to this study, the suggestions and recommendations are the usage of high speed camera should be used and placed from side view of the structure in order to check on the displacement of the structure where the LVDT could not be installed, since LVDT is not a water resistant device. Other than that, Finite Element Method (FEM) should be used rather than frame analysis for the computational analysis because in frame analysis, there are issues of overlapping of sections and materials in the modelling, affecting the overall stiffness of the structure.

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