Analysis of Hydrodynamic Forces on IBS Brickwork Structure

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Abstract. Floods have been recognized as a serious threat to both human and infrastructure. Recently, Malaysia has experienced severe flooding which led to catastrophic damage and loss of properties, and occasionally loss of human lives. This research examines the reliability of IBS Brickwork system in reducing the impacts of flooding on buildings. In this study, the behavioral performance of IBS Brickwork Structure is experimentally tested inside Dam Break Initiator (DBI) in the hydraulic laboratory using four different structural models with different walls arrangement namely; Full, Unsymmetrical, Symmetrical, and Frame-only structure. The pressure distribution and the displacement of the structure are obtained. The maximum pressure distribution in a form of concentrated force is located at lower part of the structure and the maximum displacement for the four models is 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 (is different from one to another). As a result, the infill walls play an important role in the behavior and the actions on the IBS structure during bore impact. Therefore, it is an efficient way to reduce the damage of structure during the tsunami and flood event.

Introduction

Flood worldwide has always caused grave human suffering; disruptions in normal life and activity damages, partially or entirely, of infrastructure, crops and agricultural land with severe impacts on the economy. Industrialized Building System (IBS) is an innovative technique adopted to increase the efficiency, quality and productivity of projects. In fact, (IBS) is not a new approach to the construction industry, but currently it is seen as an effective solution to improve the construction performance [1]. However, in order to implement the new IBS in the flood-prone area, there is a need for investigating the behavior of hydraulic pressure that interacts with building structure.

Recently, Malaysia has experienced severe flooding which led to catastrophic damage and loss of properties, and occasionally loss of human lives. Efforts, by both academia and industry, have been, and still ongoing, to encounter flooding events. Laboratory testing is an important concept used by engineers to find solutions to such events. IBS has never been tested for its resistance against the hydrostatic pressure generated by flooding. Therefore, it is an initiative to examine the reliability of IBS in reducing the impacts of flooding on buildings.

This study aims to obtain and analyze IBS Blockwork models in terms of pressure distribution and displacement through laboratory experiment. This research proposes to analyze and make a comparison of the experimental data obtained from the four models of IBS Blockwork (Full structure, Unsymmetrical structure, symmetrical structure, and Frame-only Structure) against the pressure distribution and their corresponding displacement for three different impounding water depth of 1.0 m, 1.50 m, and 2.0 m.

Previous Studies

Flood is a natural occurrence and considered as one the most devastating natural disasters. There are 189 river systems in the country (89 in Peninsular Malaysia; 78 in Sabah and 22 in Sarawak) all flowing directly to the South China Sea and 85 of them are less manage that may initiate flooding.

Throughout Malaysia, including Sabah and Sarawak, the approximated flood-prone zones is roughly 29,800 km2 or 9% of the total Malaysia land. Furthermore, nearly 4.82 million people which are equivalent to almost 22% of the total population of the country is affected by flood [2].

According to [3] the most common waves are the gravity waves occurring on water, and the compressibility waves that creates by moving. Following sections discuss these types of waves in more detail figure 2.1 shows, in short, the most common waves in water and air.

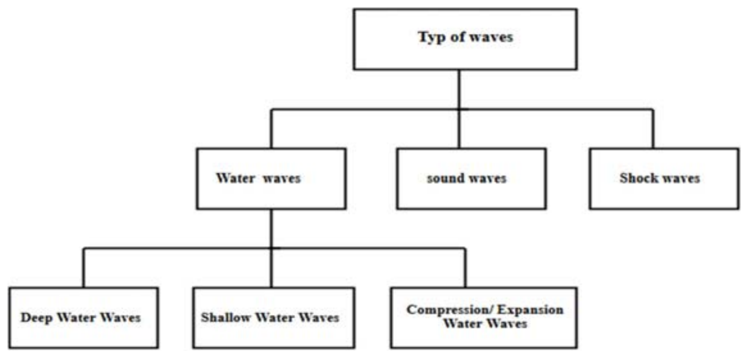

Figure 1: Types of wave in water and air

Wave Impact on Structure

There are two types of waves that severely impact the structures namely; impact waves (e.g. blast waves) and extreme waves (e.g. Tsunami waves, flood actions and Surge waves).

Blast Waves. Impingement of blast waves on structures or nearby a building can cause catastrophic damage to external and internal structural frames of a building. Blast pressure can create loads on buildings that are many times greater than normal design loads, and blast winds can be much more severe than hurricanes [4]. In short, the blast wave is not similar to water wave due to the nature of its constituent. But the effect of these wave on structure system may be similar.

Extreme Waves. Extreme waves can be in a form of flood actions, surge waves or tsunami forces in which they lead to severe damage to coastal structures /structures in all its forms. A study conducted by [5], on lateral loading on vertical structural such as columns and walls. Their experimental tests were carried out in the Tsunami Wave Basin and large Wave Flume and what they found is that it was found that forces generally increase due to the blockage of flow by adjacent columns and the solid wall.

Flood Damages

Flooding and Tsunami events are two of the most devastating natural disasters that cause damages to buildings, infrastructures and grave human casualties from their waves, debris, and surges. A study by [6] stated that, as the effects of flooding include damage to homes, shops, and industries as shown in Figure 2 which summarizes their research results.

In Malaysia, flooding has affected many areas since 1971. In 2006-2007, 2010 and 2014-2015 In December 2006 and January 200, the total cost of repair reported by Department of Drainage and Irrigation Malaysia for irrigation structures, pumps, gates, jetty, hydrological stations and others was estimated about RM260 million (USD77 mil.), while Public Works department estimated about RM147 million (USD43.6 \ mil.) for roadwork and bridges [7]. Figure 3 illustrates some of those damages. Malaysia's Experience serious flooding that impacts the economy and to society. In 2014–2015, a catastrophic flood hits Malaysia causing more than 200,000 flee from their damaged homes with total losses reaching up to RM2 billion.

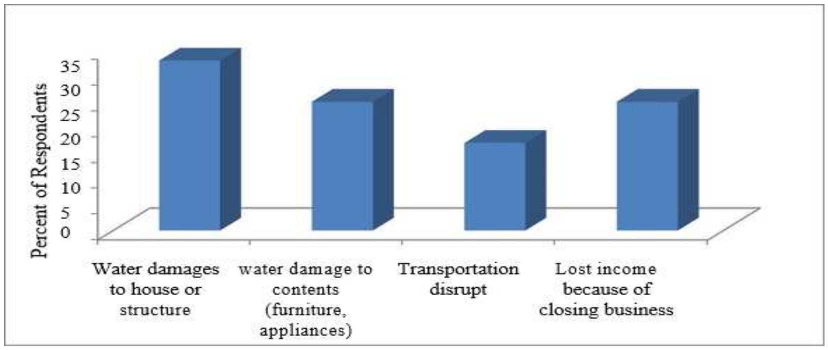

Figure 2: The four effects of flooding

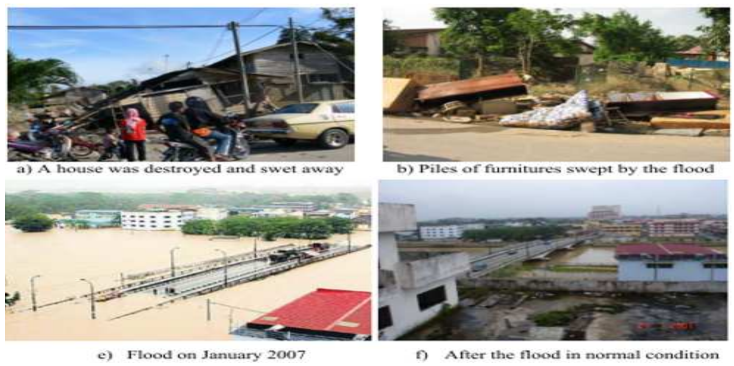

Figure 3: (2006-2007) flood damages

Applications of Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is the branch of fluid dynamics providing a cost effective means of simulating real flows by the numerical solution of the governing equations. CFD Solution/modeling is used in different industries for different analytical capabilities According to [8], CFD methods can efficiently render a better prediction of dynamic changes in flood extent.

A study investigated by [9] on the fluid actions on structure. An experimental setup carried out to determine the effect of tsunami bore forces on a wall/floor system. The experimental results were used to validate simulation of bore impact with CFD models, which can then be used to determine forces for a wider variety of situations.

Another study was conducted by [10] to compare the computed results with experimental data. It showed that RANS model reproduces the flow under investigation with reasonable accuracy while simple SWE model indicates some discrepancies. At most stages, good agreement was achieved not only in speed of negative wave front but also in prediction of free surface profiles as shown in Figure 4.

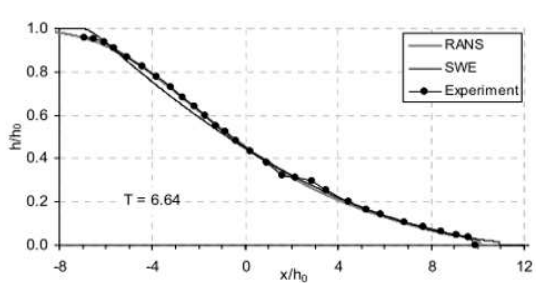

Figure 4: Computed free surface profiles comparison with the experimental data over channel at T = 6.64

Methodology

In this research a total of four main models of blockwork structures have been tested in hydraulic laboratory inside Dam Break Initiator (DBI) namely; Full structure, Unsymmetrical structure, Symmetrical structure a, and Frame-only structure as shown in Figure 5.During this experimental testing, the hydrodynamic forces (dam break effect) were released onto each of the different models of blockwork structures, and data was collected through data logger.

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

Figure 5: Blockwork structure models for (a) Full stucture, (b) Unsymmetrical structure, (c) Symmetrical structure, (d) Frame-only structure

Hydrodynamic Test

The hydrodynamic test for all four models was carried out inside a Dam Break Initiator Tank. This green colored tank in the Hydrology Lab (D02) have a flume of 2 meters wide and rotating storage tank with a holding capacity of 3 m^3 of water. It can create a fluid surge pressure of a maximum depth of 1m with a variable maximum velocity up to 7 m/s. The fluid surge pressure is considered to be the manipulated variable in this testing. Therefore, the impounding water depth is controlled in the testing. Figure 6 and Figure 7 show the building dimension and the Dam Break Initiator Tank.

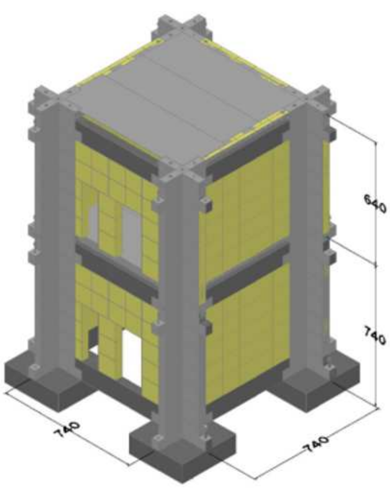

Figure 6: Building dimension

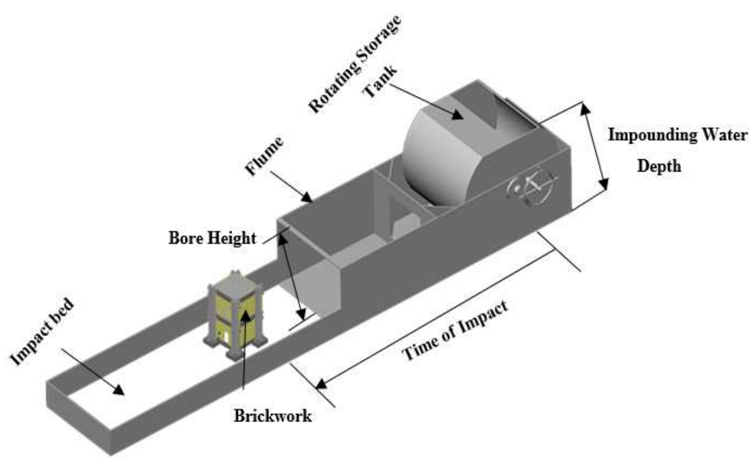

Figure 7: Dam Break Initiator Tank

There is a total of 14 pressure cells installed on the columns, bottom beam, and wall. Each of the pressure cells was numbered from 1 to 14 to track down the pressure based on its location on the structure. The pressure cell measured the water pressure on to the structure during the testing. The pressure cells were installed at the position shown in figure 8 for (full structure) and figure 9 for (unsymmetrical, symmetrical and frame- only structure).

Linear Variable Differential Transducer (LVDT) was used as the device to measure the displacement of the structure during the hydrodynamic test. As shown in Figure 10, three LVDT (50mm) was used in the testing for all 4 models.

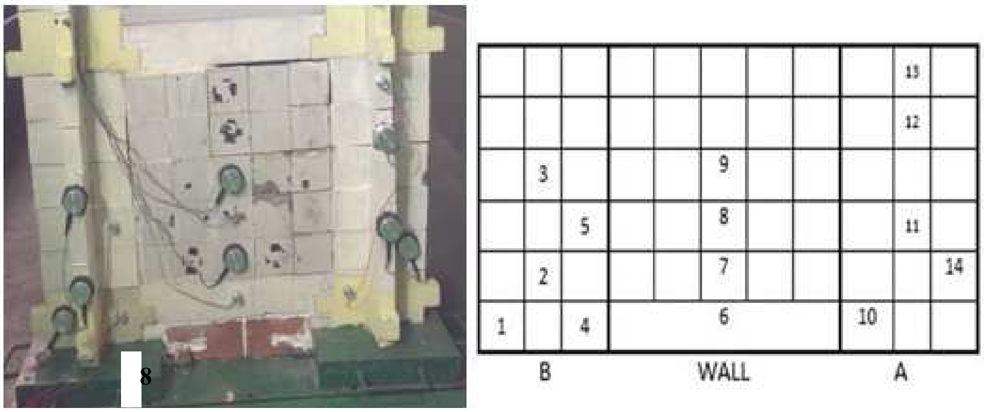

Figure 8: Pressure cell position from front view of model (Full structure)

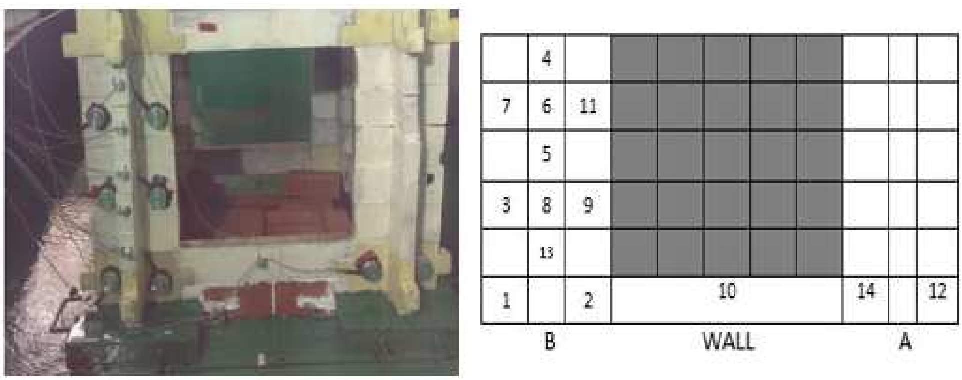

Figure 9: Pressure cell position from front view of model (Unsymmetrical, Symmetrical and Frame-only structure)

Figure 10: Position of LVDT (50mm) used for all 4 models

For each model, a test was conducted 3 times using three different impounding water depth of 1.0 m, 1.5 m, and 2.0 m in rotating storage tank. All of the pressure cell and the LVDT are connected to the data logger for all recording data where pressure reading and displacement reading can be collected and interpreted for analysis.

Result and Discussion

There were 7 testing models, but only the results from the first four models in the experiment testing are shown and analyzed in this chapter namely; Full Structure, Unsymmetrical, Symmetrical, and Frames only (Figure 5). The result consists of the pressure distribution along the front surface of the structure and also the top displacement of the structure due to the force from the water surge acted onto the structure.

Bore Induced Pressure on IBS Models

There were 7 testing models, but only the results from the first four models in the experiment testing are shown and analyzed in this chapter namely; Full Structure, Unsymmetrical, Symmetrical, and Frames only (Figure 5). The result consists of the pressure distribution along the front surface of the structure and also the top displacement of the structure due to the force from the water surge acted onto the structure.

(a) (b) (c)

Figure 11: Bore impact on IBS structure (a) 1 m impounding water depth (b) 1.5 m impounding water depth (c) 2 m impounding water depth on Unsymmetrical model

The pressures on the upstream face of IBS model were recorded using 13 pressure cells (figure 8). Based on the photos in figure 11, the height of the maximum bore pressure acted onto each model was quite distinctive. For the full structure, the maximum height of 1.0 m, 1.5 m, and 2.0 m impounding water depth were about 0.74 m, 0.88 m, and 0.93 m respectively. However, for the Symmetrical, Unsymmetrical and Frame-only Structure model the maximum height of 1.0 m, 1.5 m, and 2.0 m impounding water depth were about 0.59 m, 0.69 m, and 0.88 m respectively. The reason behind their similarity is the absence of the front wall which allows water to pass through the structure. A brief description of bore induced pressure on above-mentioned 4 models as follows:

Full structure. The pressure-time history was obtained from the data recorded by pressure cells. Figure 12 provides the pressure-time history recorded by pressure cells on this model for the impounding water depth of 2.0 m (as an illustration). The maximum pressure obtained for 1.0 m, 1.5 m and 2.0 m at the 4th s was 8.0 kPa,-16.0 kPa, and 20 kPa respectively. For all impounding water depth, the maximum water pressure occurred at the bottom center of the wall while the lowest one occurred the upper column part of the ground floor. As the bore flowed around the structure, a decrease in the force level was observed with a duration of 10 seconds.

Unsymmetrical, Symmetrical, and Frame-only structure. Similarly, the pressure-time histories was plotted by using the data recorded by the pressure cells.

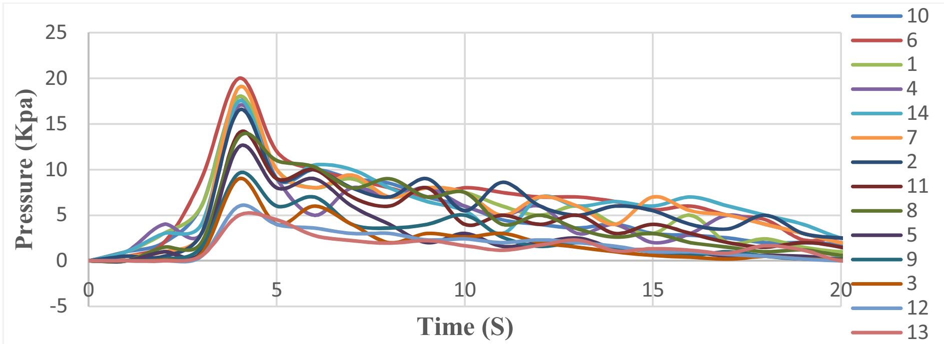

Figure 12: Pressure gauge time histories for full structure for 2.0 meter impounding water depth.

Interestingly, these models recorded almost the same maximum pressure with quasi-same pressure distribution. Figure 13 provides the pressure-time history recorded by pressure cells on this model for the impounding water depth of 2.0 m (maximum bore impact). The maximum pressure obtained for 1.0 m, 1.5 m and 2.0 m at the 4th s was 8.0 kPa,-16.0 kPa, and 19.5 kPa respectively. For all impounding water depth, the maximum water pressure occurred at the bottom beam and the inner side of the column while the lowest one occurred the upper column part of the ground floor. As the bore flowed around the structure, a decrease in the force level was observed with a duration of 10 seconds.

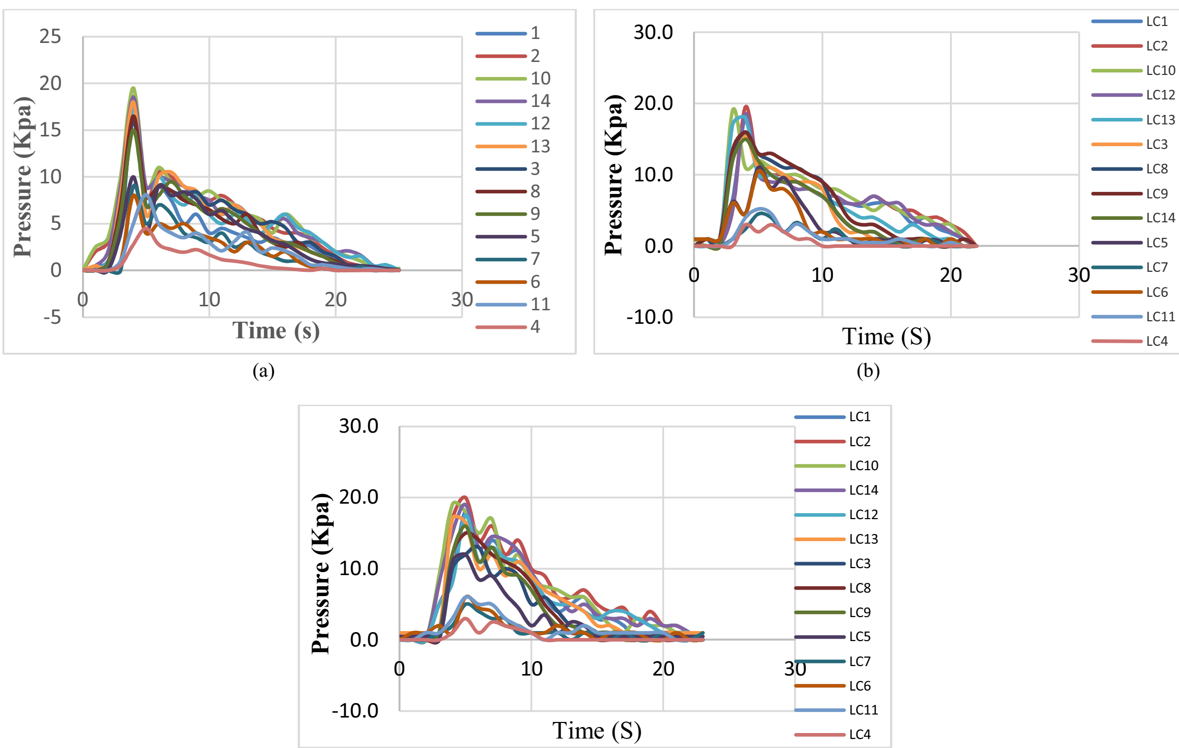

Figure 13: Pressure gauge time histories for 2.0 m impounding water depth, (a) Unsymmetrical symmetrical structure, (b) structure; and (c) Frame-only structure

Flooding Impact Force

The maximum pressure is obtained from the test that subjected to bore impact.to establish the force on structure model Figure 14 shows the division of area on the structure from the front view.

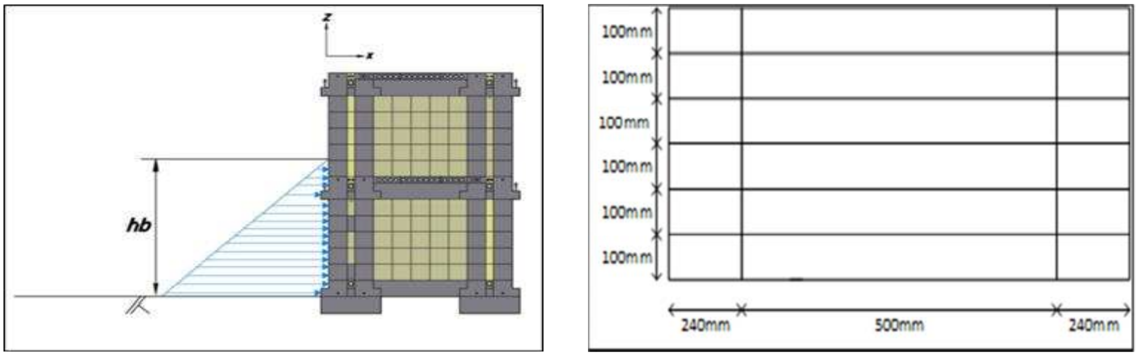

Figure 14: Pressure distribution (side-view) and subdivision area of structure (front view)

The total maximum force acted onto the structure was obtained by multiplying the maximum pressure from the pressure-time history with the area of the structure that subjected to bore impact, as shown in Equation 1. The total maximum force acted on the models as follows:

$$\max force = \sum \max pressure \times area$$

Equation 1

Full structure model. In order to obtain the maximum force acted on this model, the maximum pressure for each depth at different pressure gauge locations was obtained from the pressure time histories. The maximum force for each impounding water depth was obtained by multiplying the maximum pressure by the area of the structure that is subjected to bore impact. The maximum force for the impounding water depth 1.0 m, 1.5 m and 2.0m is 2.95KN, 6.27KN, and 7.21KN respectively as shown clearly in Figure 15.

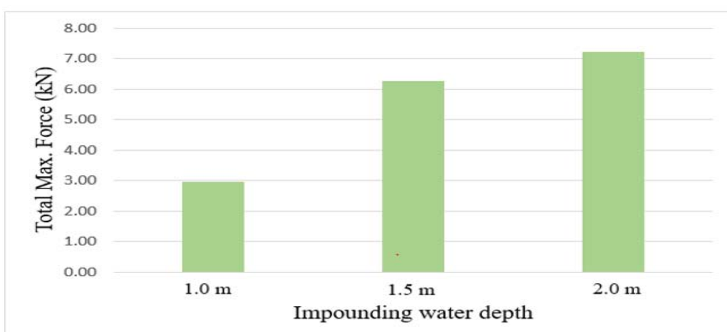

Figure 15:Total maximum force acted on the Full structure model

Unsymmetrical, Symmetrical, and Frame-only structure. In these models walls were removed partially (unsymmetrically & symmetrically) and totally (frame-only) from the ground floor of these structural models as shown previously in figure 5. Similarly, the maximum forces acted on these models were obtained by multiplying the maximum pressure recorded from the pressure time histories with the area of the structure that subjected to bore impact.

Figure 16 shows the average maximum force for the impounding water depth 1.0 m, 1.5 m and 2.0 m is 1.1 kN, 2.8 kN, and 3.60 kN respectively. The reason behind their similarity in the impacted force is the absence of the infill wall.

Response of IBS model Subjected to Bore Impact

The top horizontal displacement of the structure was obtained from the data recorded by 3 LVDT (50mm) installed at the right column (A), in the middle of the top beam (M) and at left column (B) (figure 10). The lateral displacement of the Brickwork models are illustrated as follows:

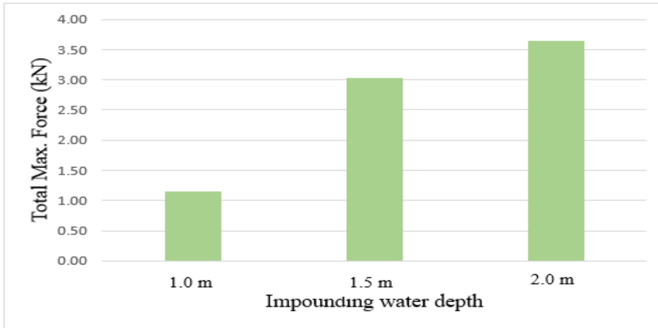

Figure16: Total average maximum force for unsymmetrical, symmetrical and frame-only structure model

*Full, Symmetrical, and Frame-only structure model.*The recorded lateral (horizontal) displacement of these models for 1.0 m, 1.50 m, and 2.0 m impounding water depth was the same for all the three LVDT as shown in Table 1 (Right, middle, and left).

A sudden rise is observed in the time history of the lateral displacement, which corresponds to the impact of the bore front on the upstream face of the structure at the 4th second. The maximum displacement obtained for 1.0 m, 1.5 m, and 2.0 m for the Full, Symmetrical and Frame-only structure model is shown in Table 1.

Table 1: Later displacement for the full, symmetrical, and frame structure model

Structure type	Water Impounding Depth (m)	LVDT Right (mm)	LVDT Middle (mm)	LVDT Left (mm)
	1.0	0.43	0.42	0.41
Full structure	1.5	0.89	0.84	0.8
	2.00	1.29	1.24	1.2
	1.0	0.33	0.32	0.31
Symmetrical	1.5	0.71	0.7	0.7
	2.00	0.95	0.94	0.94
	1.0	0.43	0.42	0.41
Frame	1.5	0.89	0.89	0.89
	2.00	1.29	1.24	1.23

*Unsymmetrical structure model.*The recorded horizontal displacement of this model for 1.0 m, 1.50 m, and 2.0 m impounding water depth was not the same for all the three LVDT as shown in Table 2 (Right, middle, and left).

Similarly, a sudden rise is observed in the time history of the horizontal displacement, which corresponds to the impact of the bore front on the upstream face of the structure at the 4th second. The maximum displacement obtained for 1.0 m, 1.5 m, and 2.0 m for the unsymmetrical structure model is shown in Table 2.

Table 2: Lateral displacement for the unsymmetrical structure model.

Water Impounding Depth (m)	LVDT Right (mm)	LVDT Middle (mm)	LVDT Left (mm)
1.0	0.5	0.3	0.1
1.5	0.78	0.5	0.3
2.00	0.9	0.7	0.5

Comparison between the maximum force between full, unsymmetrical, symmetrical and frame-only structure model

Figure 17 shows that the structure with the wall in the ground floor experience more force during the bore impact compares to structure without the wall in the ground floor. It is because the water pass through the ground floor (for unsymmetrical, symmetrical and frame) and decreases the bore impact force on the structure. Therefore, it might be a good way to reduce the damage of structure during the tsunami and flood event.

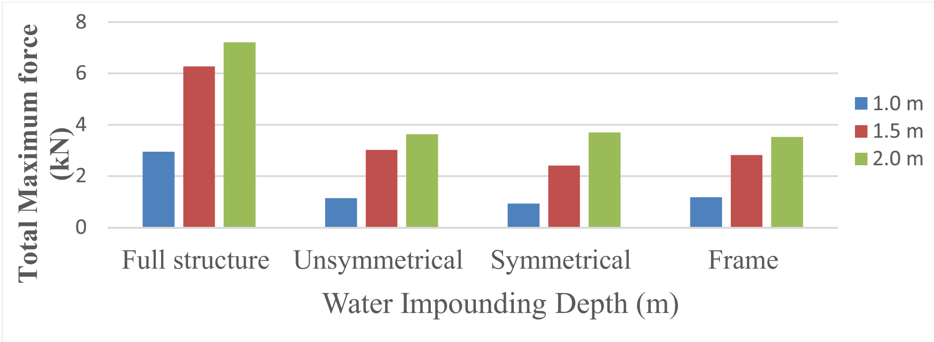

Figure 17: Reduction in the forces acted on the structures with frontal wall (Full structure and with no frontal wall (Unsymmetrical, symmetrical and frame)

Comparison between the displacement of full structure unsymmetrical symmetrical and only frame.

As seen in Figure 18 the recorded data with three LVDT for full structure, symmetrical and frame are almost same while for unsymmetrical structure the recorded data with right LVDT is more than Left LVDT. It shows that the infill walls play an important role in the lateral resistance of structure during bore impact.

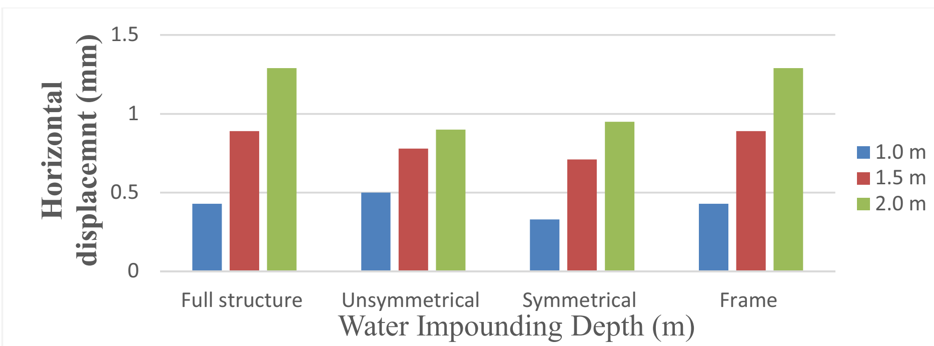

Figure 18: Lateral displacement of the Full, Unsymmetrical, Symmetrical, and frame-only structure

Conclusion

This paper presents the IBS Blockwork system as an effective defensive technique in the occurrences of flooding. Generally, the finding concludes that forces generally increase due to the blockage of flow by infill walls and adjacent columns.

In one hand, the infill walls for unsymmetrical, symmetrical and frame-only structure models play an important role in the behavior and the actions on the IBS structure during bore impact hence, it is an efficient way to reduce the damage of structures during the tsunami and flood event.

In the other hand, the displacement with the three LVDT for full structure, symmetrical and frame-only structure are almost similar, while for unsymmetrical structure, the Right displacement is more than Left displacement. This shows that the infill walls play another important role in the lateral resistance of structure during bore impact.

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