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EXPERIMENTAL INVESTIGATION OF TSUNAMI WATERBORNE DEBRIS IMPACT ON STRUCTURES

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ABSTRACT: Tsunamis and hurricanes cause a lot of damage to structures. The water-borne debris that is produced during these natural disasters can cause a considerable damage to the many structures if they have not been constructed for such loads. Tsunami field survey observations have indicated that the damage is aggravated by heavy objects like wooden logs, automobiles, boats, storage barrels and other containers. This paper presented the results of experimental study for the quantification of the debris impact force on the structures. Moreover, it studied the formulas, which have been specified in the recently published tsunami-resistant engineering design guidelines (FEMA P-646, 2012) and the Coastal Construction Manual (FEMA P-55, 2011) with the results of experiment.

Keywords: Tsunami, Hydraulic bore, Water born debris, Experimental modeling

1. INTRODUCTION

Recently, Japan witnessed the Tohuku earthquake and the resulting tsunami, which was amongst the most disastrous natural calamities. This resulted in massive losses and destruction of several structures, some of which were destroyed as a result of the high pressures generated by the tsunami wave. The investigations that were conducted on March 11, 2011, Japan Tsunami, indicated that the objects that were adrift due to the tsunami like the logs, small boats, vehicles, shipping vessels or other debris caused considerable damages to the structures and the buildings. The investigations into the damaged structures after the impact of the tsunami [1]-[5] showed that several of these structures were able to tolerate the seismic ground shaking but could not survive the tsunami load impact. The investigations further revealed that the primary cause of the damage was due to the hydrodynamic force and/or the force of the impact caused by the debris. Hence, understanding the loads caused due to the tsunamis would help in improving the design and the construction of the tsunami-resistant buildings. The design and structural guidelines that are presently followed [6]-[8] propose basic approaches describing the debris impact load; however, these are not well established.–A low-velocity impact of the higher mass of the floating debris against the civil structures has garnered more interest due to the effect of the water-borne debris like wooden logs [9]-[10], barges etc. on the bridge piers [11]-[13].

This paper focuses on the impact of the water-borne debris on the structural buildings near the shore. Furthermore, the experimental results compare with the recently published tsunami-resistant engineering design (FEMA P-646, 2012) [14] along with the Coastal Construction Manual (FEMA P-55, 2011) [15].

2. IMPACT FORCES DUE TO DEBRIS

The tsunami forces that act on the structures contain two major types of forces:

(a) Surge forces due to clear water
(b) Impact forces due to debris.

Both of these forces act together on the structures. However, of these forces, the impact forces due to the floating debris can cause maximal damage to the structures. However, the estimation of this force can be very difficult as the impact force is dependent on several variable factors.

An equation to determine the force of the impact has been proposed by the Coastal Construction Manual FEMA P-55 (2011):

$$F_i = WVC_D C_B C_{str} \tag{1}$$

Where,W refers to the weight of the debris; V - velocity of the debris,C_D, C_B and C_{str} refer to the depth, blockage, and the building structure coefficients, respectively. Out of these, the depth and the blockage coefficients vary from 0-1.0 depending on the flow depth. Meanwhile, C_{str} depends on the type of the building, the orientation, the natural period along with the duration of the impact (for the reinforced concrete walls, the $C_{str} = 0.8$). The Equation (1) is based on the impulsive momentum model and is a simple version of the original equation, which was previously described in the commentary of the ASCE 7-10. The coefficients presented in Eq.1 are based on the laboratory results and engineering judgments.

The FEMA P-646 (2012) had introduced a formula for calculating the debris impact forces, which differed from the earlier version, and it is as follows:

$$F_i = 1.3u_{\max}\sqrt{km_d(1+c)} \qquad (2)$$

Where, $\boldsymbol{u_{max}}$ refers to the maximal flow velocity near the structure. The velocity of the floating debris is hypothesised to be equivalent to the flow velocity and is decreased by almost half in case of the rolling or the dragging debris. The factor, $\boldsymbol{k}$, refers to the combined stiffness of the impacted structures, $\boldsymbol{m_d}$ refers to the debris mass, and $\boldsymbol{c}$ refers to the hydrodynamic mass coefficient, and it is seen to range between 0-1, based on the size of the debris and the orientation. According to the FEMA P-646 directives, $\boldsymbol{c = 1}$, for the debris that has a transverse orientation with respect to the direction of the flow, while the values are different for the debris depending on the type if the debris is in a longitudinal orientation. Therefore, for a wooden log debris, $\boldsymbol{c = 0}$, while for the debris like a 20-ft and 40-ft shipping containers, $\boldsymbol{c = 0.3}$ and $\boldsymbol{c = 0.2}$ respectively.

3. EXPERIMENTAL POROGRAM

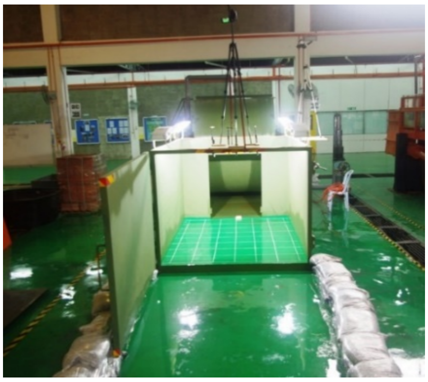
3.1 Dam Break Test

Dam break is a very popular validation case for tsunami effect study due to its simplicity of set-up with no special inflow or outflow condition is needed. Moreover, the onshore propagation of the tsunami bore is also similar to the dam-break problem [17]. In this study, the dam-break condition was achieved by impounding water in rotation reservoir tank. This tank contained two areas, i.e., the area containing the reservoir water and the flume (it refers to the model area or the impact bed area). The reservoir was a horizontal and rotational cylindrically shaped structure, which was 2 m long and had a diameter of 2.5m .On the reservoir top, there was an opening gate (2m×0.75m). During the tests, when the collected water reached the target level, the reservoir tank was rotated in a clockwise direction with the help of electrical engines, which resulted in the dam-break waves. Fig. 1 shows the view of the water reservoir.

3.2 Structural Model

Small scale (1/5) of one bay double story IBS reinforced concrete building was constructed to study the bore structure interaction and finding the debris impact force on structure. This structure has 1.48 meter height, 0.74m width and 0.74m length that introduced an equivalent 3200mm story height of building, 3700mm length and 3700mm wide of real building. Four load cells were used to measure the reaction force in IBS columns due to horizontal effect of hydraulic bore and debris impact. The load cells were attached with a load bearing plate mount. The force was then directed to the load-bearing plate, which transferred the force to the load cells. Furthermore, eight pressure cells were also fixed on the structure's upstream face for measuring the pressure time history, as described in Fig. 2. Water level gages were used to measure water level at location of structure. High speed video camera were used to record the hydraulic bore behavior, bore velocity, bore structure model interaction and debris flow velocity, orientation and impact with the structure.

(a)



(b)

Fig.1 Overview of rotational water reservoir and flume (a) side view (b) front view

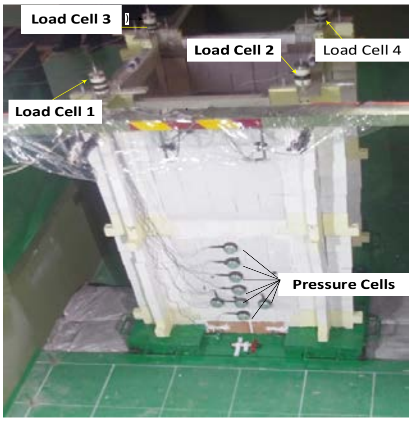
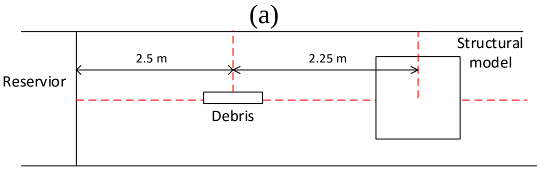


Fig. 2 Structure model and instruments

3.3 Wooden Debris

To estimate the impact caused by the wooden debris, three pieces of the wooden logs, each having differing sizes and masses, were used as three different types of debris. According to FEMA P646, 2012 [14] and ASCE 2010 [6] the mass of any wooden debris is up to 450 kg, however, according to ASCE 2010, it could even range higher than this value based on the geographical location. Therefore, the weight of debris were selected to match target masses of 4kg , 5kg and 6kg to represent the 1/5 scale of the debris as suggested by FEMA P646 and ASCE 2010 (based on Froude scaling; $\boldsymbol{M_l = \frac{M_p}{S_l^3}}$, where; M_l is the scaled mass; M_p refers to the prototype mass; S_l refers to the scale factor [18]). All this debris was marked with transverse lines at every 100 mm intervals to enable detection by the high-speed video camera recordings, as shown in Fig. 3a. The velocity of the debris flow was determined based on the time needed for the two successive transverse lines to pass from the specified flume floor section. Furthermore, the debris was also coated with thin clear plastic sheets to prevent the saturation of the logs and a resultant change in mass. Initially, all the wooden debris was kept at the centreline and the flume bottom with their sides parallel to the sides of the flume. Figure 3b shows the testing layout, which indicates the debris location and the test structure inside the flume.

(a)



(b)

Fig. 3 (a) Wooden logs of 4 kg, 5 kg and 6 kg (b) layout of test

3.4 Testing Procedure

In order to perform the test, initially, the structure was placed at the specified positions. The rotating tank was locked with the opening gate at the top position and it was then filled up with water to required level. Impounding water-depth of 2m was used in this study. The required lighting and the video camera were placed for recording the water flow and the debris movement. Thereafter, with the help of an electrical engine, the water reservoir was rotated clockwise. This resulted in the flow of water in the form of a hydraulic bore, which moved past the building structure, and then all data was recorded. Figure 4 shows a photo which was clicked during the impact of the bore on the structure.

Fig. 4 Bore impact on structure for 2m impounding water depth in water reservoir

To determine the impact of the debris on the structures, the wooden log was placed at the flume floor at a pre-specified distance from the structure before every test, as shown in Fig. 3b. Once the bore progressed downstream, it resulted in an increased flow and movement of the debris, resulting in its impact against the building structure. The impact of the debris and the velocity was determined using video camera recordings, as indicated in Fig. 5.

t=2.110 s

t=2.340 s

t=2.570 s

Fig. 4 Snapshot of 6 kg wooden debris impact on structure

4. RESULTS AND DISCUSSION

4.1 Time History of Tsunami Bore on Structure

The time histories of column reaction forces, i.e., RF1, RF2, RF3 and RF4, based on the bores generated due to the water impoundment depths of, h_0= 2 m, have been illustrated in Fig. 5. It shows the sudden increase in the reaction forces, which depended on the first contact between the bore and the structures' upstream face. There is a primary spike in the force when the turbulent bore edge impacts the structure, which decreased when the bore moved past the structure. This lasted for 8-10 secs.

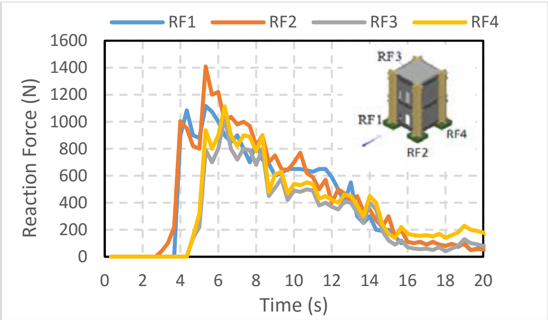


Fig 5 Experiment data for time history of bore forces of 2m impoundment depth

4.2 Debris Impact Forces

Figure (6) depicts an example of the time history of reaction column forces for a tsunami bore with a wooden debris weighing 4 kg, that was recorded using the load cell 1 i.e., RF1. An instant rise was noted in the force values at t= 6.33s and the force reached the value around 1000N based on the bore impact. The figure illustrates that when the debris hits the structure, there is an increase in the column reaction force, which reaches values higher than the clear bore. It was also noted that, sometimes, there was a rebound action of the wooden logs, which impacted and struck the buildings for the second time, resulting in two different force peaks. As the second force peak was lower than the initial peak, the first peak was chosen as the maximum force.

Figure. 7 illustrates the time histories of the impact forces against the structure, which were measured using load cells, caused due to the bores bearing wooden debris and impact that was generated with impounding water of depth, 2 m. An instant rise was noted for the recorded forces at t= 6.33s, 6.5s and 7s for the wooden debris of 4, 5 and 6 kg respectively.

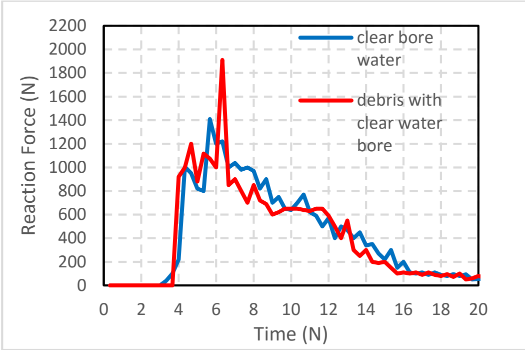
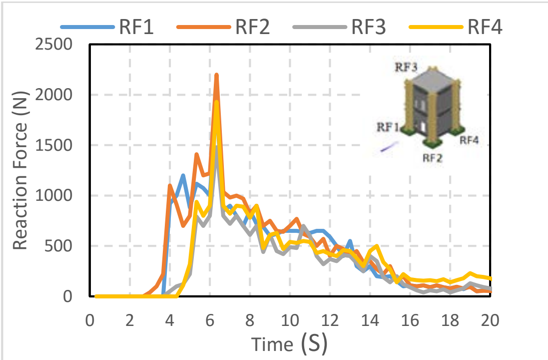
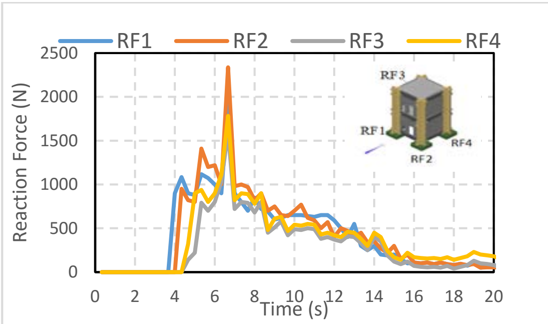


Fig 6 Comparison of clear water bore force and water bore with 4kg debris forces (recording data with load cell1 (RF1))



(a)



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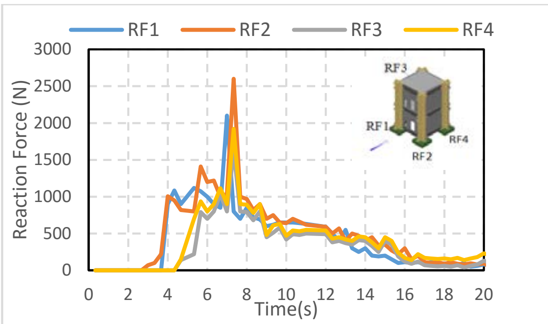

(c)

Fig 7 Experiment data for time series of bore forces and debris impact on structure (a) 4kg (b) 5kg(c) 6 kg

Table 1 Reaction force of structure due to bore and debris impact

Reaction Forces	Recording data for reaction forces (N)at t=6.33s			Recording data for reaction forces (N) at t=6.5s			Recording data for reaction forces(N) at t=7s		
	Bore without debris (A)	Bore with 4kg debris (B)	Only debris B-A	Bore without debris (A)	Bore with 5kg debris (B)	Only debris B-A	Bore without debris (A)	Bore with 6kg debris (B)	Only debris B-A
RF1	900	1910	1010	850	1950	1100	900	2100	1200
RF2	1000	2200	1200	1037	2337	1300	980	2600	1620
RF3	1035	1480	445	800	1600	800	720	1620	900
RF4	1114	1920	806	900	1783	883	820	1920	1100
Total	4049	7510	3461	3587	7670	4083	3420	8240	4820

It can be seen from Fig. 7 and Fig. 5, that there was a significant increase in the base shear force due to debris impact. This demonstrates the significance of determining the maximal forces of the debris impact against the structures. The force of the debris alone may be estimated by assuming that the force of the bore is the same both with and without debris. Table 1 depicts the relative bore force with debris and that of the debris alone.

The debris impact force is influenced by the parameters like the mass and the velocity of the debris. This experimental data indicated that the debris with lighter weights needed lesser depth for floating and could thus move at higher velocities, while the heavier debris needed larger depth of water, and moved at lesser velocities. The velocities that were determined for the weights measuring 4, 5 and 6 kg were 1.4, 1.3 and 1m/s respectively.

Figure (8) illustrated the experimentally estimated values of the debris impact forces on the structure and they were calculated with the help of the formulas provided in the design guidelines. FEMA P-55 (Eq. 1) with the assumptions the largest value for coefficients C_D and C_B equal to 1 and C_{str} =0.8 (which is intended for reinforced concrete walls) were investigated to determine the impact force of 4kg, 5kg and 6kg of this study. The force depicted in Fig. 8 is based on the experimentally determined debris velocity. Figure 8 also depicts the estimated debris impact forces using FEMA P-646 (Eq. 2). FEMA P-646 has proposed C=0 and k=2.4×10^6 for wooden log debris. Figure 8 shows a good agreement between the values calculated using formula recommended by FEMA P-646 and the experimentally determined values, especially in the case of bigger debris. It also illustrates that after using Eq.1, the values of the debris impact force was lower than by using FEMA P-646 (Eq. 2) and the experimental values. The values using FEMA P-55 (Eq.1) were lesser than even 10% of those obtained by experimental results. This discrepancy in the results could be dependent on the fact that Eq.1 does not consider the effective stiffness between a debris and structure.

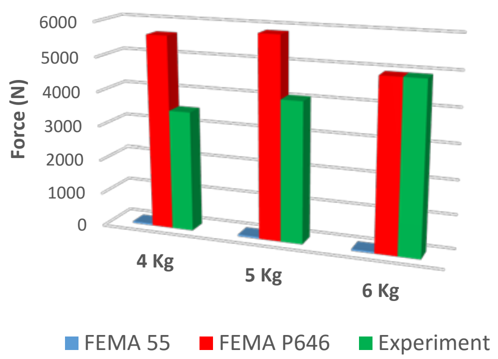

Fig. 8 Comparison of waterborne debris-impact forces

5. CONCLUSIONS

This study determined the debris impact forces and the tsunami-bore forces on structures, which are affected by the tsunamis. Moreover, this paper tried to estimate the time-series hydrodynamic forces on the structures, which are impacted by the rapidly progressing hydraulic bores, which are like the coastal floods resulting due to the tsunamis in qualitative manner. This study then compared experimental results with the equations that have been proposed by the FEMA P-55(2011) and the FEMA P-646 (2012). After the comparison, it was noted that the equation proposed by FEMA P-55 greatly underestimated the values of the impact forces. However, the equation proposed by FEMA P-646 provided a better and more accurate estimate of the impact forces.

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