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A STUDY ON DAMMING AND BUOYANT FORCE ON 4-STORY REINFORCED CONCRETE FRAME

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Abstract

A number of buildings collapsed under huge tsunami caused by 3.11 Earthquake mainly in the coast of Tohoku area. The government established a new design guideline of the tsunami evacuation buildings after the earthquake, which suggested the accurate evaluation of the tsunami load and the building strength. The new guideline contains the hydrodynamic force, buoyant force and counter measure for the soil erosion by the scouring and the impact by waterborne debris, but it does not refer the additional force on openings by the damming of water borne debris.

This study reports on the hydrodynamic tests on reinforced concrete specimens with a model of dammed waterborne debris. Test specimens simulates the tsunami evacuation tower, and 1/10 scale 4-story reinforced concrete moment resisting frame. The test specimen is 330 mm in story height and 650 mm in width. Each story was composed by columns and beams of 45 mm square section and 15 mm width floor slab. The super structure of the specimen is constructed over the concrete base foundation, which is embedded under the ground surface. The lateral wave force and buoyant force are measured by the waterproof loadcells under the base foundation. The waterborne debris is 900×720×700 mm timber boxes, which modeled Japanese traditional two-story timber houses. The hydrodynamic test is carried out in the largest water flume in CRIEPI. The maximum load of induced wave was designed to occur in the subsequent flow after the surge front. The waterborne debris is settled in front of the test specimens, and the specimen collapsed with beam-side sway mechanism by the damming force, while the specimen survived without the water borne debris under same induced wave. It estimates the lateral wave force on the specimen by the empirical formula of (a) drag force and (b) summation of the hydrostatic force in front of and behind the specimen based on AIJ design guidelines for tsunami load. The accurate estimate is derived from the summation of the hydrostatic forces.

The maximum buoyant force is evaluated from the water density and the submerged volume of the specimens. The total weight of the specimen increases in the hydrodynamic test, although the buoyant force acts on the specimens in upward direction. The inside of load cells is vacant and it excludes the inflow of water. The water weight over the load cells increases the weight of the specimen without hydro pressure from the bottom, and it exceeded the buoyant force due to the volume of the super structure.

Keywords: tsunami, waterborne debris, hydrodynamic test, damming force, buoyant force

1. Introduction

Many buildings were destroyed and washed away by the 2011 Great East Japan Earthquake especially in the Tohoku region [1]. The maximum inundation depth of the tsunamis exceeds 10m, and 3-story or 4-story reinforced concrete buildings also overturned, while more than 4-story buildings are designated as tsunami evacuation buildings in case of over 3m tsunamis in the past design guideline at that time. The ministry of Land, Infrastructure, Transport and Tourism published the new design guideline for tsunami evacuation buildings based on the post tsunami damage survey result after the earthquake, and it shows the practical method of structural design calculation in this guideline [2].

However, the guideline does not define a certain impact force by the water borne debris, but instead it shows indirect design solution that assumes the loss of a column due to the impact of the debris and does not cause the building to collapse. AIJ recommendation for Load on Buildings (2015) [3] proposes the several formulation of the impact loading force by the waterborne debris although the effect of the impact force on the building response has not been studied.

Also, the guideline does not refer the additional force on openings by the damming of water borne debris. The design guidelines promote the open frame and reduce the design tsunami load on the buildings based on the damage survey result that the timber or reinforced concrete structures with large openings often survive under 2011 Great East Japan Earthquake. however, it may cause the underestimation of the tsunami load especially on those tsunami evacuation towers due to the damming of the waterborne debris.

The guideline proposes a method for calculating an effective buoyancy acts on the building when water flow into the buildings, but the proposed model has not been validated by the experimental data or the damage survey result. Tsunami loads on complex shaped structures such as building structures have been verified mainly since 2011, and the number of hydrodynamic tests on building structures is very limited in past researches. AIJ recommendation refers to the water weight inside of the building in addition to the weight and buoyancy of the building, and the vertical force acting on sumerged buildings should be verified by the hydrodynamic tests with the building specimen.

In this study, it compares the wave load on the reinforced concrete skeleton frame with and without waterborne debris in front of the specimen [4], and evaluate the incremental load on the openings by damming effect in the hydro dynamic tests in 1st test series. In 2nd test series, waterborne debris were drifted from the upstream to make an impact load on the specimen. In 3rd test series, the static water level change gradually without flow and the buoyant force on the specimen is investigated by the water-proof load cells.

2. Test specimen

Fig.1 shows the plan and elevation of the test specimen. The test specimen is one-tenth scale four story reinforced concrete frame structure. The specimen has square floor plan with four columns. The span length and the story height of the specimen are 650 mm and 330 mm. Fig.2 shows the section of the members. The column and beam section are 45mm square, and thickness of the floor slab is 25 mm. It has two kinds of specimens, which has different longitudinal reinforcement in columns and beam sections. Four 2.2 mm micro rippled rebar are used for columns and beams in low-strength specimen. 4 mm micro rippled rebar are used for columns and beams in high-strength specimen. Eight reinforcing bars were arranged in the column cross section, and Four reinforcing bars were arranged in the beam cross section. 2 mm micro round rebar is used for the transverse reinforcement of columns and beams with 15 mm spacing. 4 mm rippled rebar is placed on the floor slab section with 20 mm spacing by single layer in both directions, and it cut off at the side surface of the transverse beam sections, in order to make the beam strength simple to calculate.

The bottom of 1st story columns are connected to the concrete base foundation embedded under the water flume bed. It has 30 mm clearance between the base foundation and water flume bed, which was fulfilled by static water before the hydrodynamic test. The concrete base foundation was supported by the four water-proof load cells fixed to the water flume. The material property is shown in Table.1. Concrete strength is 42 N/mm^2, and yielding of 2.2mm and 4 mm rippled rebar is 234 and 373 N/mm^2. The specimens are designed to collapse in 1st story collapse mechanism. The lateral load carrying capacities are 2.04 kN for the low-strength specimen, and 5.78 kN for the high-strength specimen in calculation. The strength of the specimens is verified by the static cyclic loading test, and load-displacement relations are shown in Fig.3. The lateral force is applied at the height of the 2nd floor in the test. The maximum strength is 2.63 kN for the low-strength specimen, and 7.25 kN for the high-strength specimen. A comparison of the test result with the calculation results shows good agreement.

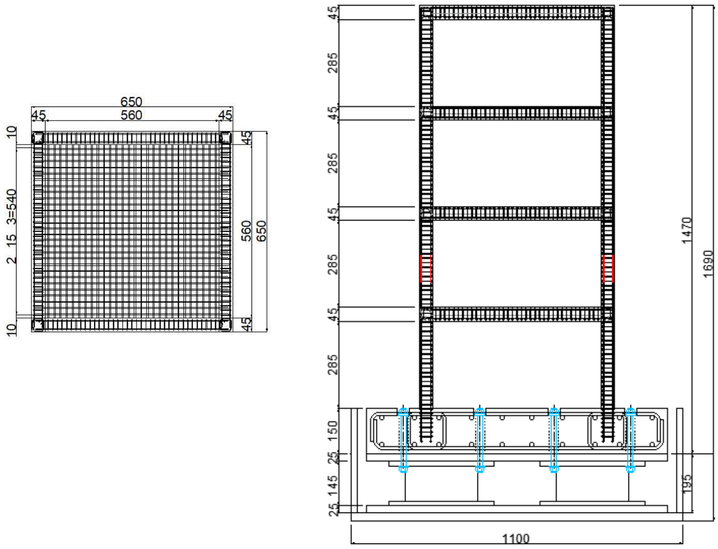


Fig. 1 – Plan and elevation of the test specimen (unit mm)

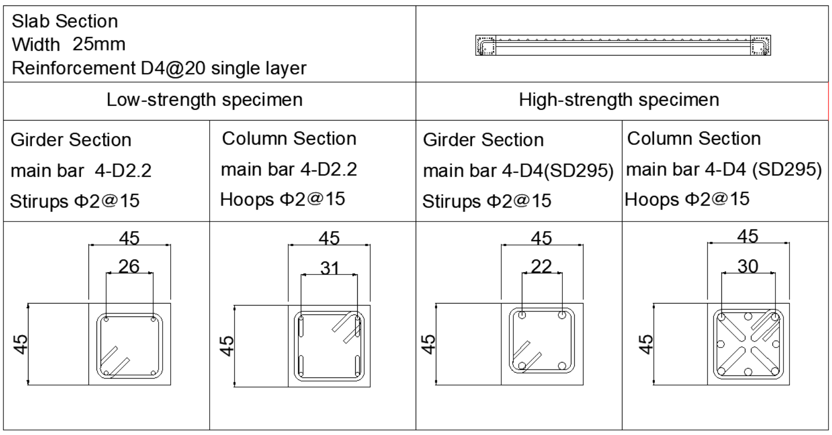


Fig. 2 – Section list of the test specimen (unit mm)

Table 1 – Property of the materials

	Cocrete Compressive Strength			Steel Tensile Strength		
	High-strength Specimen	Low-strength Specimen	Rebar	Tensile yielding stress (N/mm^2)	Max. tensile stress (N/mm^2)	Max. tensile force (kN)
1F	38.0	40.9				
2F	42.6	46.9	D4	373 N/mm^2	508 N/mm^2	7.14 kN
3F	42.7	41.8	D2.2	234 N/mm^2	338 N/mm^2	1.29 kN
RF	45.4	47.7	ϕ2	621 N/mm^2	723 N/mm^2	2.27 kN

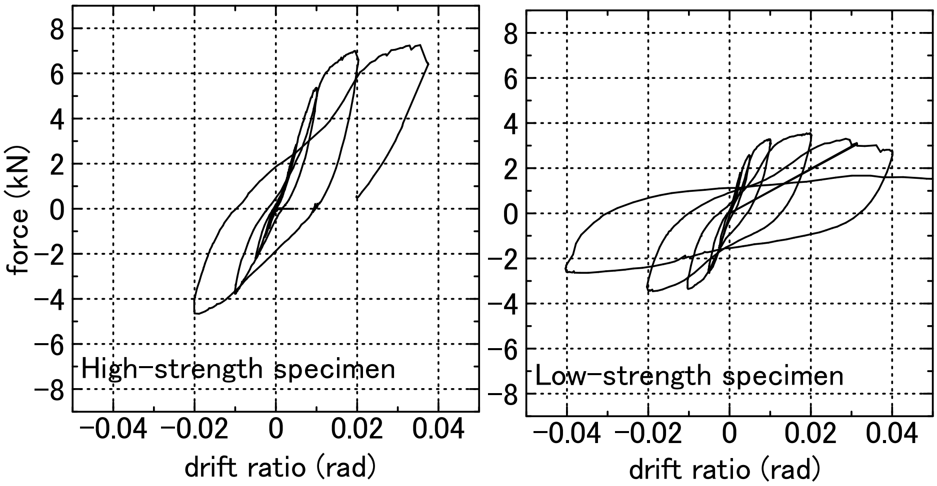


Fig. 3 – Load-displacement relation in the static loading test

The waterborne debris is two kinds of timber box frames assembled with 12 mm concrete casting form panels. Photo.1 shows the overview of the waterborne debris used in the hydrodynamic test. The original model of the waterborne debris is 2-story timber residential house with 65 m^2 floor space and 3.5m story height. The outer shape is 900×720×700 mm. It has the steel weight inside anchored by bolts at the bottom of the timber box. The total weight of the box is 113kg and 220kg.

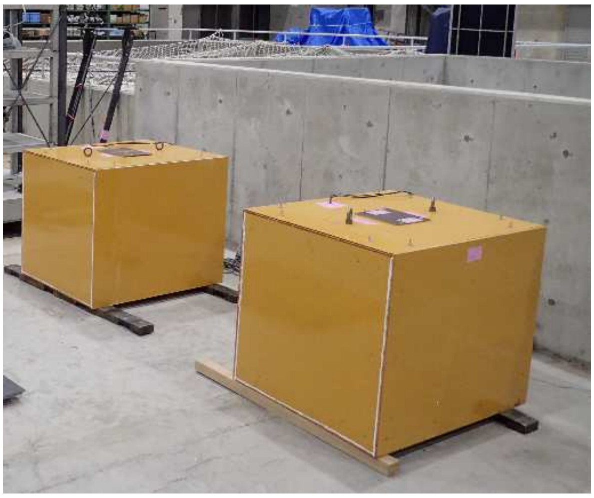


Photo. 2 – Waterborne debris

The hydrodynamic test was carried out at the largest water flume in CRIEPI. Fig.4 shows the section of the water flume. The inflow water is controlled by the water gate electrically so that the inundation depth gradually increases. The test facility can simulate the subsequent flow behind surge in tsunami, and the impulsive wave load does not affect the building response, which is often observed in hydrodynamic test with soliton waves using the piston-type wave maker.

The specimen was initially submerged to a depth of 0.2 m in order to increase the maximum wave load in the test. The total wave load on the specimen is evaluated by four water-proof load cells under the specimen. The lateral drift at the roof of the test specimen is measured from the backward by the laser displacement meter. The wave pressure is measured by the pressure gages on the column surface in each story. The water level and velocity in steady flow are measured 5.5 m ahead of the test specimen by ultrasonic sensors. The front and rear water levels of the columns are also obtained by the wave pressure gages at the column bottom.

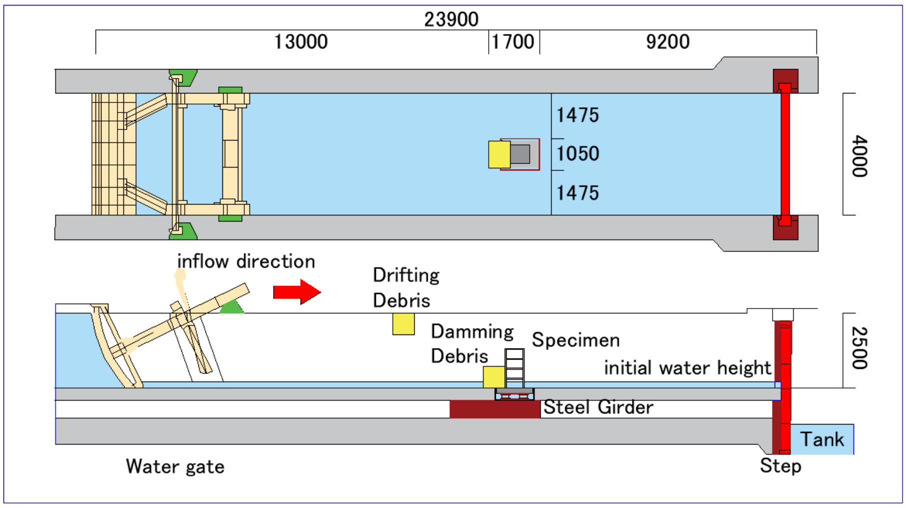


Fig. 4 – Section of the water flume (unit mm)

3. Damming force by the waterborne debris

In 1st test case series, the wave load on the specimen is compared with and without the debris settled in front of the low-strength specimen. Table 2 shows the maximum water level, wave force and flow velocity in two test cases. The intensity of input wave is similar and the specimen survived both in these tests. The time history of wave load and water depth is shown in Fig.5. The maximum wave force is recorded before the water level become its maximum. The maximum water depth is about 0.85 m and Froude number is 0.84 in the flow. The maximum wave load in the hydrodynamic test with the debris is approximately 5 times the value in the hydrodynamic test without the debris. The maximum wave load exceeds the maximum strength in the static loading test, but the specimen survived in the hydrodynamic test. It is because that the measured wave load includes the contribution of the wave pressure in lower part of 1st story, and it does not affect the collapse load of the upper structure. Fig.6 shows the wave pressure distribution on the column surface. The wave pressure is measured in the front and backward section of the specimen by pressure gages in case of the hydrodynamic test without waterborne debris. The pressure gages are attached to the middle height of the columns in each story. The wave pressure has triangular distribution when the wave load is the maximum. The wave pressures in front and backward frame is similar, but pressure in backward reduces due to the obstruction of the front frame.

Table 2 –Hydrodynamic Test Result (Damming force of the debris)

Test Case	Debris Direction	Damage	Wave Load (kN)	Water Depth (m)	Flow Velocity (m/s)	Froude number
Low-strength Specimen	None	Survived	0.57	0.852	2.418	0.834
High-strength Specimen	Horizontally Placing	Survived	2.77	0.857	2.448	0.842

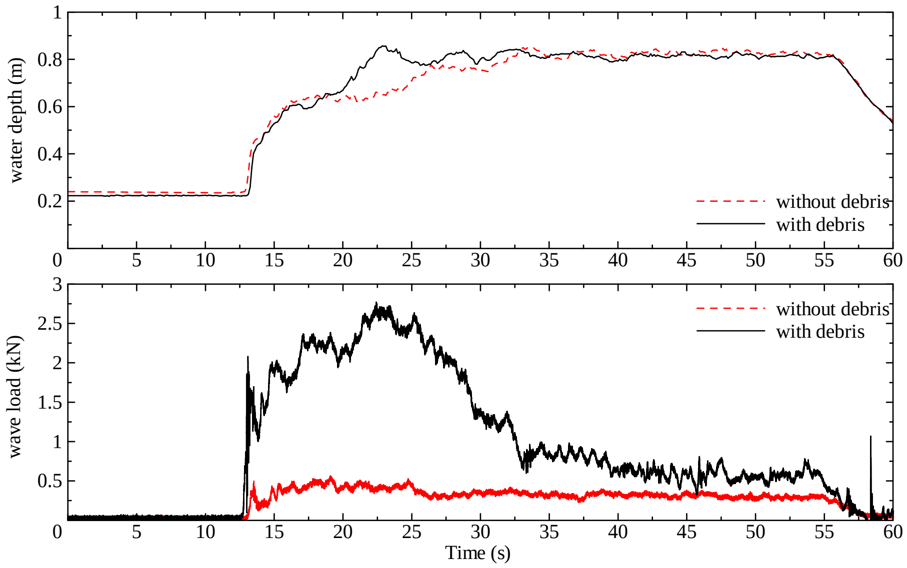


Fig. 5 – Time history of the water level, flow velocity and wave load in the hydrodynamic test

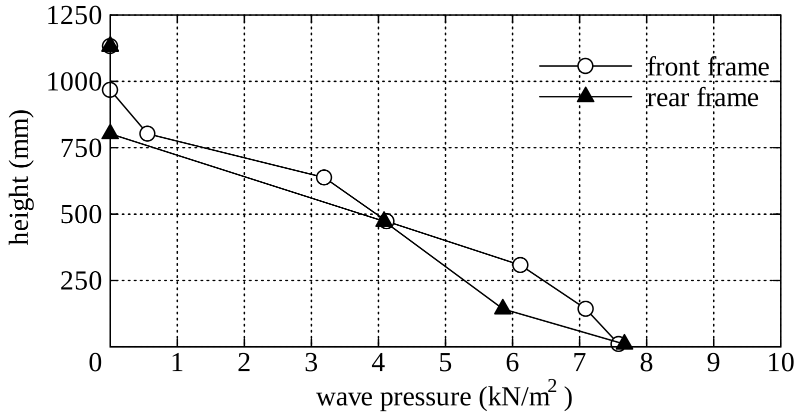


Fig. 6 –wave pressure distribution in the hydrodynamic test

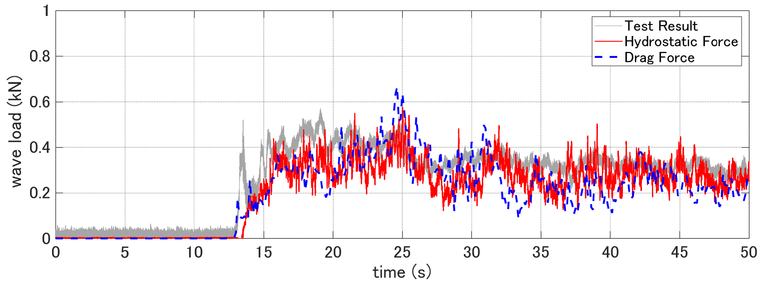
Drag force and the summation of the hydrostatic force are compared with the wave load in the hydrodynamic test. Drag force is evaluated by Eq. (1) using the water level and flow velocity 5.5m ahead of the specimen. The wave pressure is in proportion to the square of the flow velocity and distributed uniform. The drag coefficient is 2.05 for the rectangular column shape in calculation. The hydrostatic force is evaluated by Eq. (2) using the front and rear water levels of the columns obtained by the wave pressure gages at the column bottom. Wave pressure is in proportion to the water level and distributed in a triangular shape. Hydrostatic force acts in the flow direction and opposite direction in front and rear frames. The wave pressure integrates in the horizontally projected area of the test specimen, and it ignores the wave pressure on openings.

$$F_v = \int_0^{h_i} \frac{1}{2} C_d {v_i}^2 B(z)\, dz \quad (1)$$

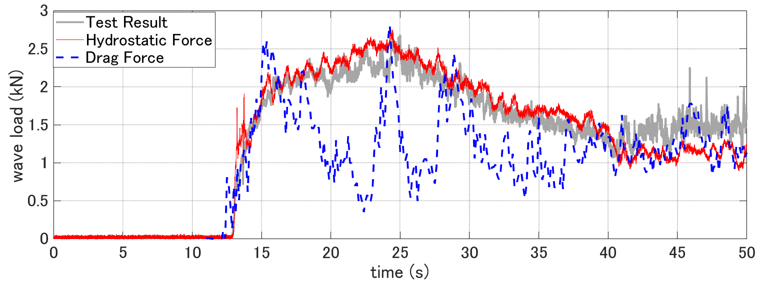
$$F_h = \int_0^{h} \rho g (h-z) B(z)\, dz \quad (2)$$

Here, F_v: Drag force, F_h: Hydrostatic force, h_i: Inflow water level, C_d: Drag coefficient, v_i: inflow flow velocity, B(z): Width of the test specimen at height z, h: water level at the column surface, ρ : water density, g: gravity acceleration

The time history of wave load, drag force and the summation of the hydrostatic force are shown in Fig. 7. The hydro static forces are consistent with the test result in entire time history, while there are several time zones with large errors between the drag forces and the test result. It is because the flow velocity and water level fluctuate and the measured value are not representative of the entire flow. The maximum load of the drag force is in agreement with that of the test results.



(a) test without the debris



(b) test with the debris

Fig. 7 –Time history of the wave load in the test and calculation

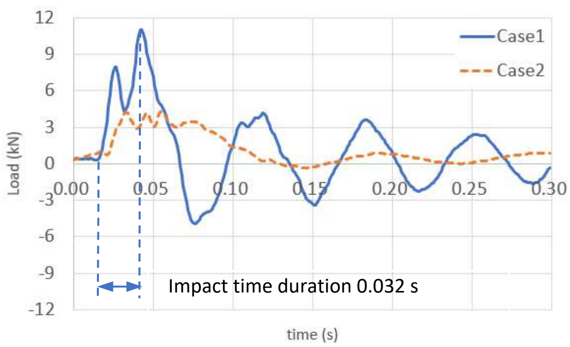
4. Impact force by the waterborne debris

In 2nd test case series, the debris was drifted from 3m upstream 30 seconds after the start of the flow, and it hits the test specimen approximately 5 seconds later. Test results are listed in Table 3. Heavy debris hits the high strength specimen (Case1), and light debris hits the low strength specimen (Case2). The input flow is same. The water depth and flow velocity are 0.91m and 1.76 m/s in the subsequent flow after the surge. The time history of the impact loads and the displacement of the roof is shown in Fig.8. The maximum wave load is 11kN in Case1, and it exceeded the yielding strength of the test specimen in the static loading test. However, the maximum displacement is negligible because the impact loading time is very short (0.026 s). The maximum wave load also exceeded the yielding strength of the test specimen in Case2, and 1.4% drift was observed in the impact loading test. The relation between load and displacement is compared in the static loading test and the impact loading test in Case2. The stiffness and the yielding strength are large in the impact loading test, and the response force oscillated during the nonlinear response.

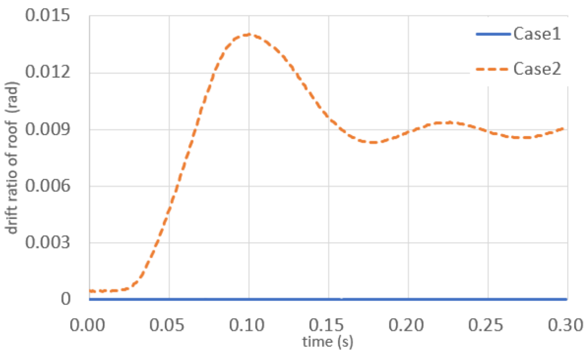
The elastic impulse capacity of the specimen is evaluated from the yielding strength and natural circular frequency corresponding to the secant stiffness of the yielding point in the static loading test. The yield point of a specimen is defined as the restoring force reaches the design yield strength in a static load test as shown in Fig.9. The mass of the specimen was calculated from the volume of the specimen, assuming that the density of the concrete was 2.4 ton / m^3. The capacity of the elastic impulse is 0.111 kNs in Case1, and 0.033 kNs in Case2. The input impulse due to the impact can be calculated from the debris mass and the velocity loss obtained by integrating the debris acceleration during impact. The input impulse is 0.120 kNs in Case1 and 0.094 kNs in Case2. The input impulse is about 3 times the elastic impulse capacity of the specimen and nonlinear response is observed in Case2, while the input impulse is same with the elastic impulse capacity and it remains the elastic response in Case1.

Table 3 – Hydrodynamic Test Result (Impact Load of the debris)

Test	Specimen M=0.147 ton	Yielding stiffness K_y	Impulse capacity $Q_u/\sqrt{K_y/M}$	Debris	Input Wave	Load (kN)	Drift (rad)	Velocity Loss ⊿V(m/s)	Input Impulse ⊿MV (kNs)
Case1	High-strength Q_u=5.78kN	401 (kN/m)	0.111 (kNs)	Heavy 0.210 ton	Depth 0.91 m Velocity 1.76 m/s	11.03	0	0.57	0.120
Case2	Low-strength Q_u=2.67kN	640 (kN/m)	0.033 (kNs)	Light 0.113 ton		4.37	0.014	0.83	0.094



(a) test without debris



(b) test with debris

Fig. 8 –Time history of the wave load and displacement in the impact loading tests

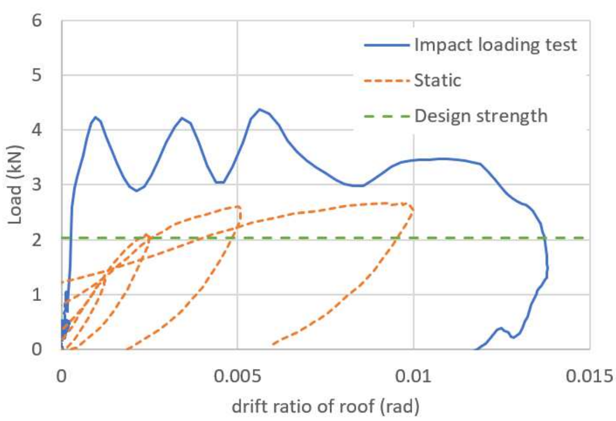


Fig. 9 –Load-displacement relations in the impact loading test (Case2) and the static loading test

5. Buoyant force on the frame structure

The buoyant force on the frame structures is investigated in the hydrostatic test. The static water level change from 1.23m to 0.05m gradually without flow. The relation between water level and vertical force is shown in Fig.10. Initial vertical loads are considered to be zero and positive values indicate compression. The measured vertical loads decrease as water level decreases in the test, although the buoyant force will also decease by changing water level. This test specimen is supported by four water-proof load cells, which anchors to the water flume. The inside of the load cells excludes the water inflow and there is no buoyant pressure in the area of load cells. It means that the weight of water above the load cells acts vertically downward on the test specimen. Fig.11 shows the relation between the water level and the vertical load after subtracting the varying water weight over the load cells. The estimate of the buoyant force from the water level and the volume of the test specimen is also shown in Fig.11 by the dotted line. When the water level decreases in the hydrostatic test, the vertical force increases due to the decrease in buoyancy. The estimate is slightly lower, but consistent with the measured vertical load. It indicates the inflow water weight acts vertically downward until the water flow under the building due to scouring or liquefaction of the ground. The buoyant force can be evaluated by the submerged volume of the buildings after water flow under the building.

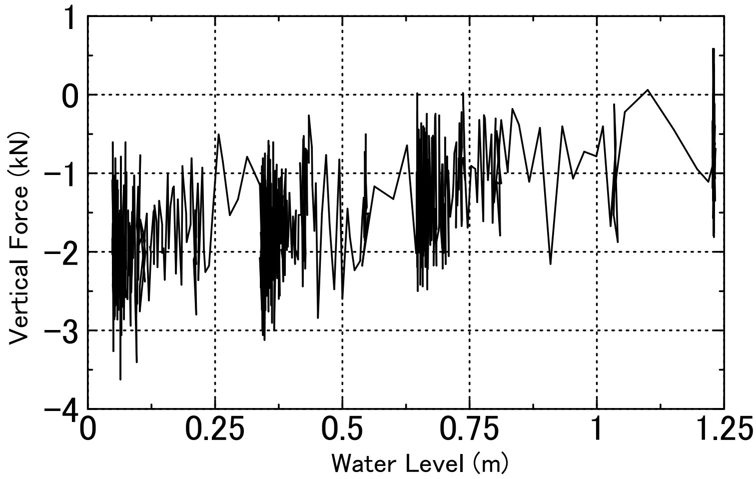


Fig. 10 –Time history of the measured vertical forces in the hydrostatic test

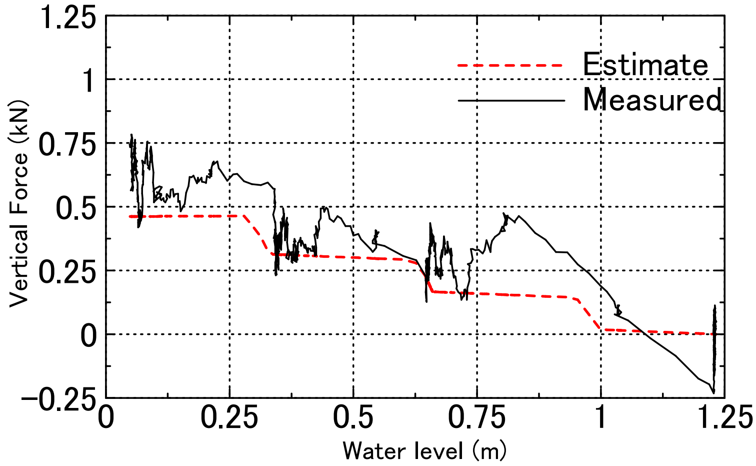


Fig. 11 –Comparison between the measured and the estimate of the buoyant force

6. Conclusion

The study shows the nonlinear response of the reinforced concrete frame specimens with the waterborne debris in hydrodynamic test and static loading test. The following conclusions may be drawn from these test results:

- The wave loads of the 4-story reinforced concrete frame with the damming debris increases five times as much as a frame without the damming debris in the hydrodynamic test. The wave pressure distribution is triangular shape at the time the wave load is maximum. The time history of the wave loads is consistent with the summation of the hydrostatic forces, while there are several time zones with large errors between the drag forces and the test result.
- Large deformation of the low strength test specimen caused by impact load, while the high strenrth test specimen remains elastic in the impact loading test. The maximum impact loads exceeds the yielding strength of the specimens in both tests. The input impulse is about 3 times the elastic impulse capacity of the low-strength specimen, while the input impulse is same with the elastic impulse capacity of the high-strength specimen.
- Buoyant force can be evaluated by the submerged volume of the reinforced cocrete frame in the hydrostatic loading test. The weight of water above the load cells acts vertically downward on the test specimen, because the water does not flow under the load cells.

7. Acknowledgements

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8. References

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