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Performance of Soft-first-story Buildings against Earthquake Motions and Tsunami Loadings

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Abstract

A series of earthquake and tsunami loading tests of reinforced concrete buildings with soft-first story were conducted to identify the effects of earthquake shaking preceding to the tsunami loading, which might cause the collapse of the structure. The dynamic and hydraulic tests were conducted in 2014 and the static tests in 2015 totally for five specimens out of six specimens constructed. Three specimens were tested at hydraulic testing laboratory at PARI, Kurihama, in the first series of 2014 under earthquake loading and tsunami loading. The first specimen with 50 mm square column was tested under hydraulic loading with water height of 1.0 m and survived the hydraulic loading without collapse. The second specimen with the same dimensions of 50 mm square was subjected to dynamic loading first with the maximum acceleration of 0.4 G and then the same tsunami loading of 1.0 m, in case the specimen collapsed totally under hydraulic loading. The third specimen with 75 mm square columns survived the same shaking and the tsunami loading with minor damage. In 2015, the static lateral loading were conducted to bare specimens of two types and also the survived specimen with 75 mm square columns, from which rigorous and accurate hysteretic relations under static loading could also be obtained. The effects of seismic loading on the capacity against the following tsunami wave are discussed in details with the observed behavior as well as with the calculated capacity.

Keywords: Tsunami loads; Shaking table test; Collapse capacity

1. Introduction

A number of building structures in Tohoku Coastal Area are washed out by Tsunamis on 2011 Great East Japan Earthquake. In severely damaged area such as Rikuzen-Takata, Onagawa, and Minami-Sanriku, the maximum inundation depth of Tsunamis exceeded 10 m and low-rised steel or reinforced concrete structures shows story collapsing or overturning in induced tsunami direction, as well as timber structures [1].

Japanese Government settled the design code of the tsunami evacuation buildings based on the damage observation results or past research of coastal engineering after the earthquake [2]. The strength of the tsunami evacuation building is confirmed following this design method, so that the design strength has to be higher than the maximum impulsive surge front wave force and dynamic lift forces observed under extremely special condition in past hydro dynamic tests [3], although all of survived buildings do not always have so much high strength in the damage observations. This high design criteria makes it difficult to prevail the construction of the evacuation buildings in special dangerous area subjected by Tsunamis.

Authors has been conducted the basic hydro dynamic test on the plain reinforced concrete wall in the past research [4]. The dynamic lift forces was applied on the bottom of the specimens as an additional overturning moment, while the synchronism between lateral force and the dynamic lift force is not obvious in the overturned specimen. The strain gages on the tensile rebar does not respond to the impulsive wave force in the test. This test result implicated the behavior of the reinforced concrete structures under tsunamis, although it may change by the scale of the test, the collapsing mechanism, and dynamic characteristic of the wave load.

In 2011 Great East Japan Earthquake, 1st story collapse mechanism is also typical damage pattern among steel or reinforced concrete buildings as well as the overturning of the buildings at the base foundation. In this study, the effective tsunami load on the building in collapsing process is evaluated by large-scale hydro dynamic tests on the reinforced concrete soft first story building. The hydro dynamic test facility has the shaking table under the water lane, and the effects of the residual seismic damage on the dynamic response under tsunamis are discussed in details.

2. Specimen

The elevation of the specimens are shown in Fig.1. Specimens are one-tenth scale soft first story structures which idealized a five story reinforced concrete building, and has four columns and wide opening only on 1st story. Two types of specimens (S1 specimen, S2 specimen) has different columns on 1st story (diameter 50 mm and 75 mm), while the upper structures are identical. The scale size of test specimens is too small for the shaking tests because of the capacity of the hydrodynamic test facilities in this research. Correlation between dynamic responses of tests and frame analytical model should be compared in further study. The number of columns is also insufficient for a standard design plan of reinforced concrete buildings. In this test, it assumed that the original building has a number of sections in transverse direction such as Japanese traditional apartment houses, so that the specimen has only four column in order to equalize the wave load per frame with those buildings

The upper structure is box-shape, and consist of walls and slabs with a thickness of 75 mm. The transverse partition wall and slab supported at the middle of the wave pressure receiving wall in order to prevent the concrete cracking in the hydro dynamic test. Wall and slab sections has doubly arranged D4 rebar with 100 mm spacing. The width of the specimen is 1250 mm in longitudinal direction, and 650 mm in span direction. The total height of the specimen is 1600 mm, and the clear span of the 1st story columns is 300 mm. The reinforcing bar at the bottom of the 1st story columns are anchored 200 mm inside the mat foundation. The mat foundation has 300 mm thickness, and the top surface of the foundation is same height with the ground level. It is separated from the surround ground soils with 150 mm gap so as not to transfer the shear force. The surrounding gaps are covered by the steel plate so as not to inflow the water. The self-weight caisson concrete placed on the shaking table, which fixed the mat foundation of the specimen through four water proofing load cells. The height and width of the caisson is 1.5m and 2.14 m. The load cells measured the shear and axial load on the specimen. The calculated weight of the upper structure is 12.40 kN, and that of the mat foundation is 18.40 kN.

2.2 mm rippled steel rebar are arranged as longitudinal reinforcement in the column section. The yielding stress of the rebar is 302 N/mm^2. Each columns has ϕ2 round steel rebar hoops with 150mm spacing. The maximum strength of the concrete is 30 N/mm^2. The story collapse mechanism is designed in the ultimate state of the specimen. The ultimate moment strength M_u of the 1^{st} story column is calculated by formula (2). The maximum strength of the plastic hinge mechanism Qu is derived from formula (4) with M_u. Qu is 4.71 kN for S1 specimen, and 7.70 kN for S2 specimen [5].

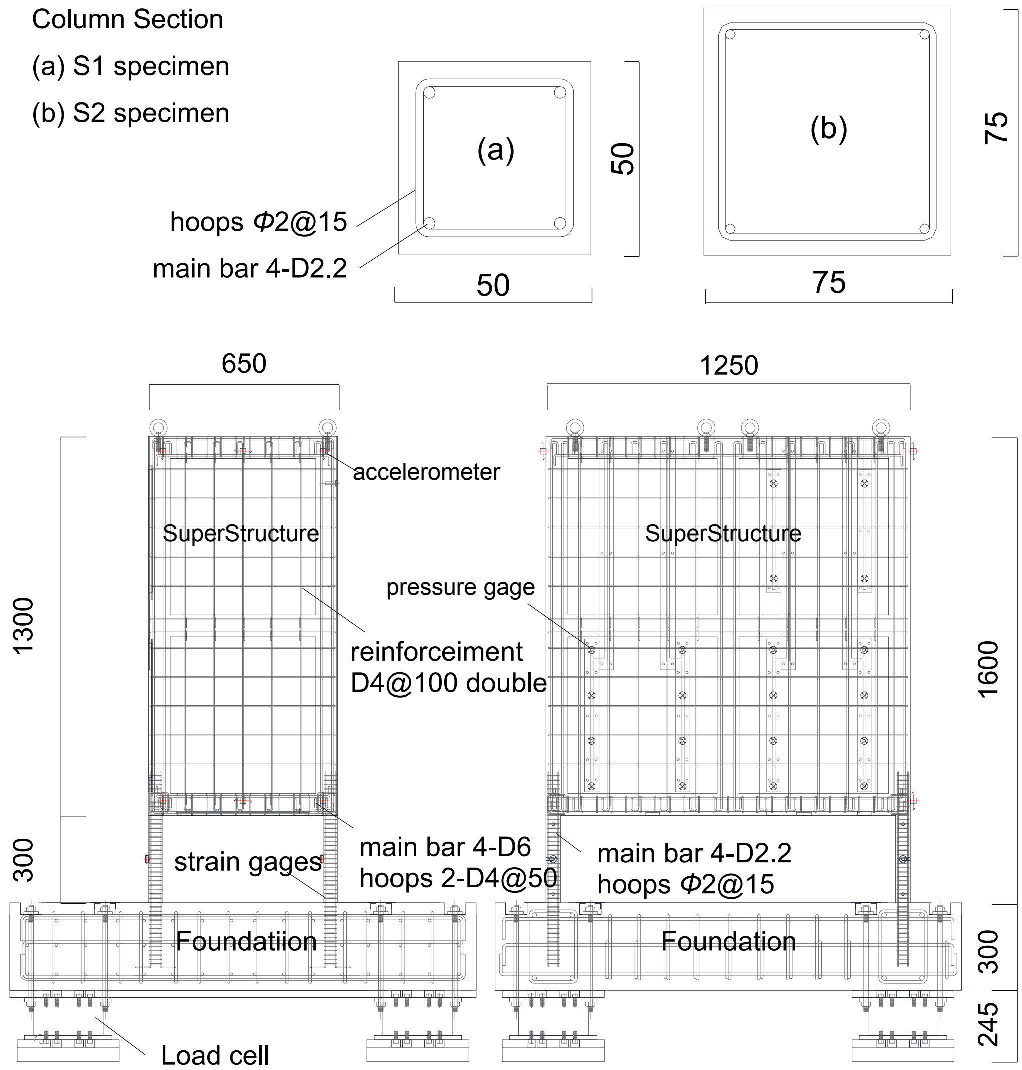


Fig. 1 –The elevation of the Specimens (unit: mm)

Table 1 – Material Test Result (N/mm^2)

Concrete	Reinforcement (D2.2)		
Compressive Strength	Yield Strength	Tensile Strength	Young Modulus
30	302	323	122700

$$M_c = 0.56\sqrt{\sigma_B} \cdot Z_e + N \cdot Z_e / A_e \tag{1}$$

$$M_u = 0.8 a_t \cdot {}_s\sigma_y \cdot D + 0.5 \cdot N \cdot D\left[1 - N/(\sigma_B \cdot D^2)\right] \tag{2}$$

$$Q_c = \sum_4 (2M_c / H) \tag{3}$$

$$Q_u = \sum_4 (2M_u / H) \tag{4}$$

Here, Q_c:Cracking shear strength, Q_u:Ultimate shear strength, M_c:Cracking moment strength, M_u:Ultimate moment strength, σ_B:concrete strength, Z_e:equivalent section modulus, N: axial load, A_e:equivalent section area, a_t:tensile reinforcment area, ${}_s\sigma_y$: yielding stress of reinforcement, D: width of a column, H: 1st story height

Table 2 – Calculation Strength of the Specimen (kN)

S1		S2	
Qc	Qu	Qc	Qu
2.40	4.71	6.80	7.70

Six water pressure gages are located in 400 mm, 556 mm, 812 mm, 968 mm, 1213 mm, and 1539 mm height from the ground level. Those gages are fixed in the acryl plate, which is embedded in the concrete wall. The pore water pressure gages is attached at the middle of the 1st story column as an additional measurement. The vertical water pressure is also measured on two points at the ceiling plane of 1st floor (163mm far from the gravity center point). The lateral deformation at 1300 mm and 1550 mm height is measured behind the specimen with laser displacement meter. Vertical and lateral accelerations are measured at the top, 1st floor level and base of the specimen as well as the mat foundation. 12 strain gages are located on top and bottom of the column section in front and backward frame. The water level and flow velocity is measured in front of the specimen by the electromagnetic water gage and propeller type current meter.

The hydro dynamic test has been carried out in the Large Hydro Geo Flume at PARI in Fig.2. The length, width and depth of the flume is 184 m, 3.5 m, and 12 m. The specimen and the shaking table under the flume is 130 m away from the wave maker. 1/8 slope is arranged in front of the specimen by compacting the improved soil, which fixed the concrete caisson and the mat foundation.

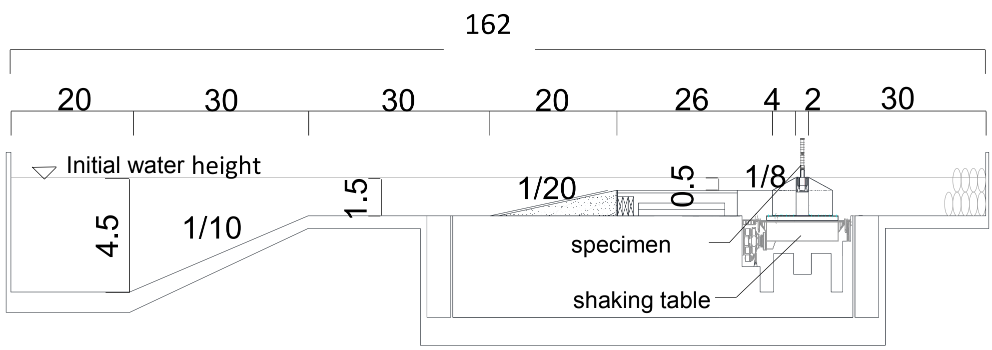


Fig. 2 – Large Hydro Geo Flume (PARI) (unit: m)

2. Hydro Dynamic Test

Three kinds of input soliton waves are provided in the water flume. The maximum water height is 0.6m, 0.8 m and 1.0 m, and the period of the wave is 20 seconds. The time history of water height are shown in Fig.3. Three kinds of input ground motions are provided on the shaking table, which are (a) K-net Ishinomaki records in 2011 Great East Japan Earthquake, (b) K-net Ojiya records in 2004 Niigata-Chetsu Earthquake, and (c) Sin wave (5Hz or 10Hz). The amplification factors for the input accelerations is determined by the preliminary analysis results so as to give a certain nonlinear deformation by the seismic load.

2.1 Water test without object

Water test without specimens has been carried out before the hydro dynamic test. Time history of the water height and velocity at the specimen installation planned position in Fig.3. Two kinds of waves (800mm height, and 1000 mm height) are tested. Froude number of the wave is 1.13 for 800 mm height wave and 1.17 for 1000 mm height wave. In the hydrodynamic test, a ratio of water height dammed by the specimen to that in the water test is 1.39 for 800 mm wave and 1.53 for 1000 mm height. This value is smaller than estimate with the maximum Froude number and simple Bernoulli's theorem. This is due to the large opening in the 1st story.

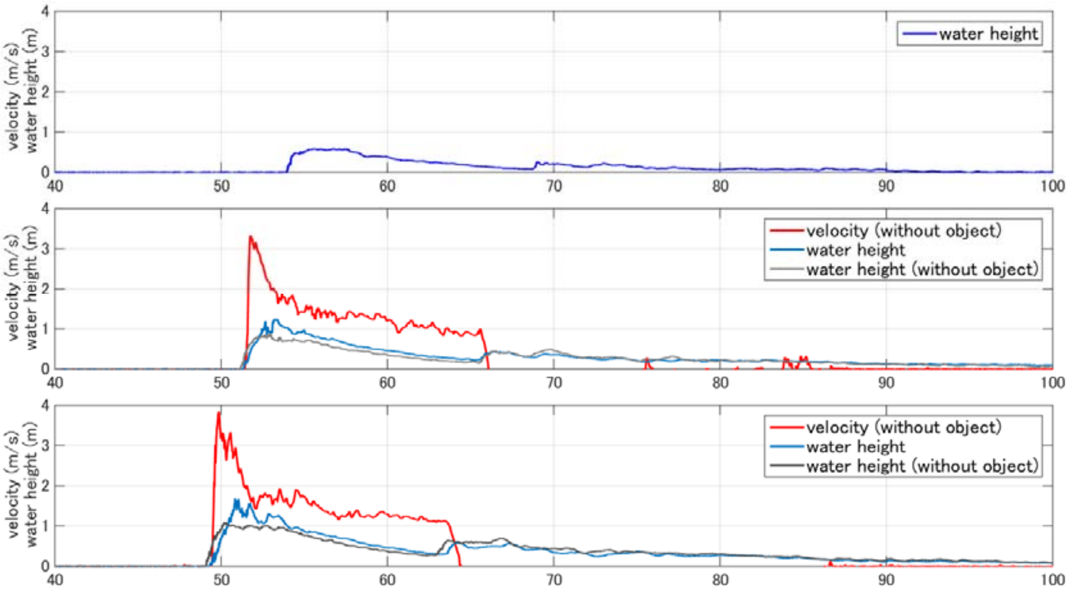


Fig. 3 – Water test result

2.2 Damage of the Specimen

Run table of the test is shown in Table 3. Two identical S1 specimens (S1A and S1B) are collapsed by the maximum height tsunami wave load, and S2 specimen survived under the maximum height tsunami wave load. Different loading path was given to the identical two specimens. S1A specimen survived under 0.8 m and 1.0 m height tsunami without shaking test. Most of longitudinal reinforcement of 1st story columns yielded under 0.45G Ishinomaki records. The specimen collapsed by the 1.0 m height tsunami wave load. On the other hand, S1B specimen suffered similar damage on columns firstly by the shaking test of 0.45G Ishinomaki records without a hydro dynamic test. The specimen collapsed by the 1.0 m height tsunami wave load after the shaking test as well as S1A specimen. S2 specimen, which has larger size columns, survived under hydrodynamic test after the shaking test, while the specimen shows quite a large story drift in the shaking test. It indicates that structural performance of the specimen exceeded the capacity of the water flume.

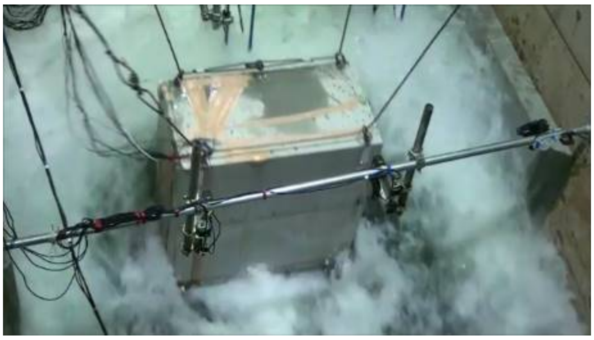
Table 3 – Run Table of the Hydrodynamic Test

Specimen	S1A	S1B	S2
RUN1	Wave 800mm	Ishinomaki 50gal	Wave 600mm
RUN2	Wave 1000mm	Ishinomaki 450gal	Wave 800mm
RUN3	Ishinomaki 350gal	Wave 1000mm (Collapse)	Ishinomaki 315gal
RUN4	Wave 800mm		Ishinomaki 600gal+ Wave 1000mm
RUN5	Ishinomaki 450gal		Ojiya 400gal
RUN6	Wave 800mm		Ojiya 450gal
RUN7	Wave 1000mm (Collapse)		Wave 1000mm
RUN8			Sin Wave 5Hz 200gal
RUN9			Sin Wave 10Hz 300gal
RUN10			Wave 1000mm

(a) S1A Specimen before the test

(b) S1A Specimen with tip of the wave (RUN1)

(c) S1A Specimen with steady stream (RUN1)



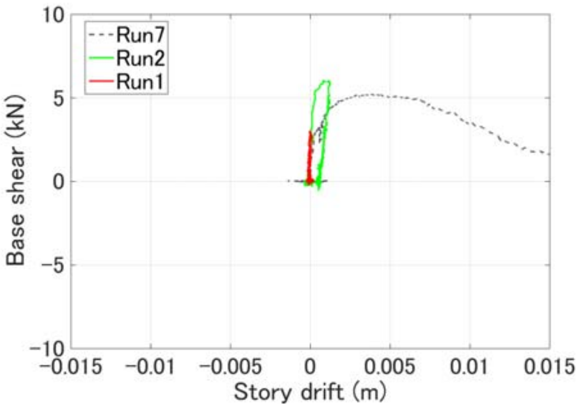
(d) S1A Specimen with tip of the wave (RUN7)

Fig. 4 – Hydrodynamic test results

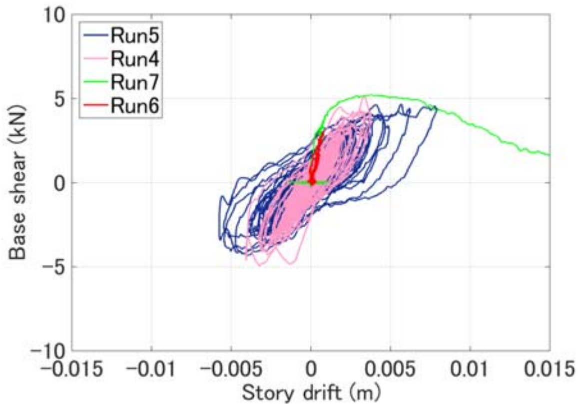
2.2 Load-Displacement Relation

Load displacement relation of the specimens is shown in Fig.5. S1A specimen shows the maximum strength 6 kN in the hydro dynamic test at RUN2. The maximum story drift of the specimen reaches 0.008 m under the sequential shaking and hydrodynamic test after RUN2. At the collapsing hydrodynamic test (RUN7), the yielding strength is 1kN smaller than the maximum strength at RUN2 as well as the previous test result. The hysteretic curve shows strength deterioration after yielding. The maximum strength at RUN2 is far larger than lateral load carrying capacity in calculation (4.7 kN) and it indicates the yielding stress of reinforcement increases for the effect of strain velocity. The specimen has been damaged by sequential shaking tests and the yielding strength under wave load has been saturated with the calculation strength. The effect of buoyant force on the moment strength of the columns is very small in this test. The maximum wave load has been recorded at the tip of the wave, and the maximum lateral force and buoyant force was not recorded simultaneously.

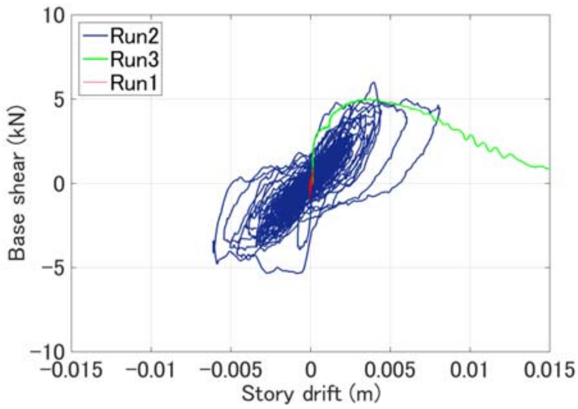
S1B specimen has been suffered damaged by the shaking test at RUN2 and the maximum story drift also reaches 0.008 m. The specimen collapsed under 1000 mm height wave load as well as S1A specimen. The backbone curve of shaking test and hydrodynamic tests are identical, and the maximum strength is consistent with the calculation value. The strain velocity effect on the reinforcement is observed only in wave loading test. On the other hand, S2 specimen shows almost same strength under hydrodynamic tests at RUN2, RUN7, and RUN10, while the damage of the specimen has been progressed by the shaking test. This is simply because the the maximum wave load is smaller than the yielding strength of the specimen (7.7 kN). The hysteritic curve at RUN9 shows unsteady shape. This is because the displacement at the base foundation included the nonlinear response of the surrounding ground soil damaged by the resonance of the base foundation in the shaking test.



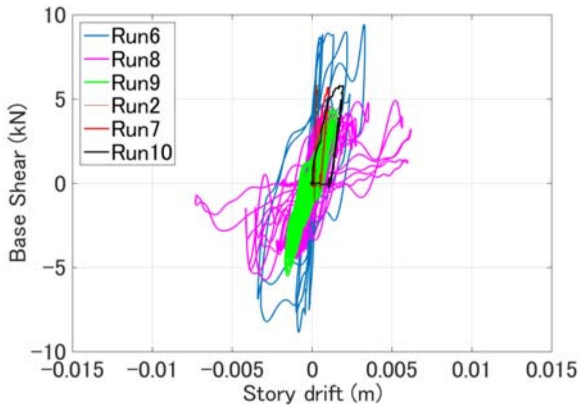
(a) S1A Specimen (RUN1&2)



(b) S1A Specimen (RUN5~7)



(c) S1B Specimen (RUN1~3)



(d) S2 Specimen (RUN2~10)

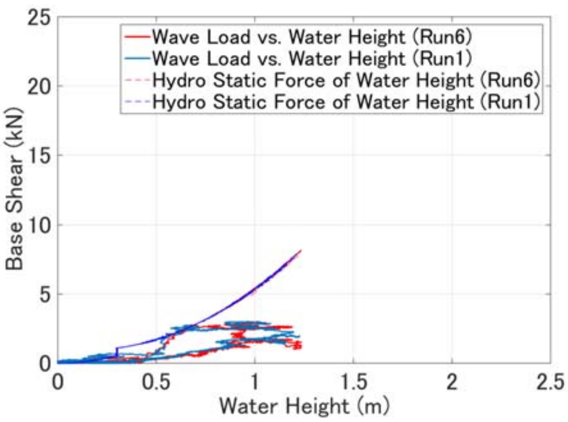
Fig. 5 – Load displacement relation in the hydro dynamic test

2.3 Water height and wave load relation

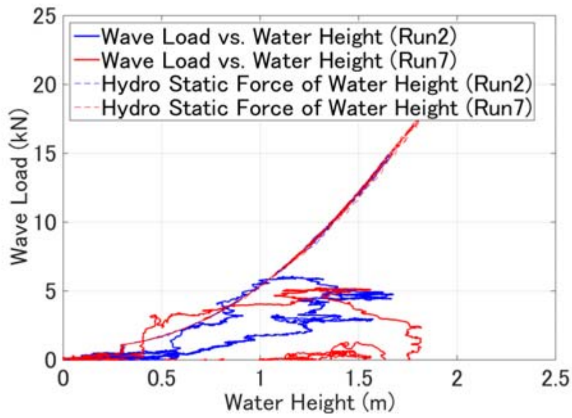
The relation between water height and wave load is shown in Fig.6. One-direction hydrostatic force evaluated by the water height in front of the specimen is also described in dotted line. This hydrostatic force shows identical value with the wave load if there is no water behind the specimens. It is because this value reflected the increment of water height due to the afflux dammed by the specimens. In calculation of hydrostatic force, the contribution of wave pressure on openings is ignored. The wave load on S2 specimen at RUN1 is very small in comparison with other cases. Wave pressure on large openings is negligible and it demonstrates the effectiveness of the soft first story in design of tsunami evacuation buildings.

The wave load is far smaller than the hydro static force after recording the maximum wave load. It seems the effect of negative wave pressure in backward surface on total wave load is negligible because Fig.4 disproved the existence of water on backward surface of the specimen. This is because the wave pressure shows smaller value as approaching the side surface, and the integrated value of the wave pressure does not represents the hydrostatic force of water height in the central position of the specimen.

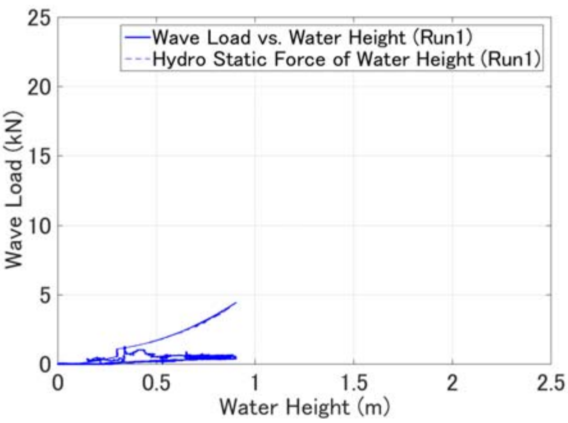
The test result of S1A specimen shows different wave loads in survived case (RUN2) and collapsed case (RUN7). This is because the base shear includes the inertia force of the specimen in collapsed test case. The hysteretic curve of the specimen in survived cases shows almost identical path.



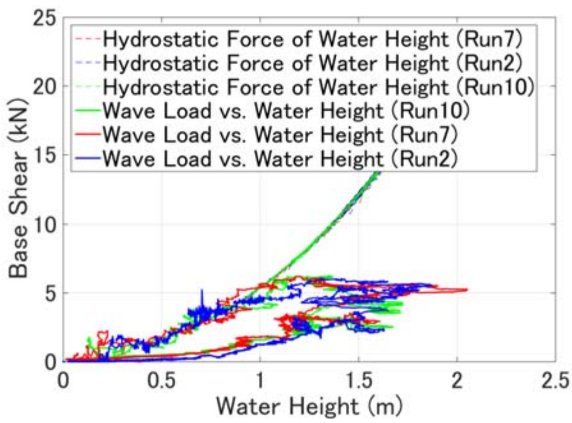
(a) S1A Specimen (RUN1&6)



(b) S1A Specimen (RUN2&7)



(c) S2 Specimen (RUN1)

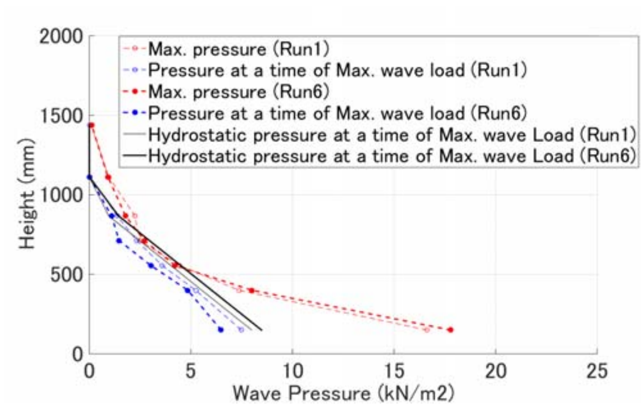


(d) S2 Specimen (RUN2&7&10)

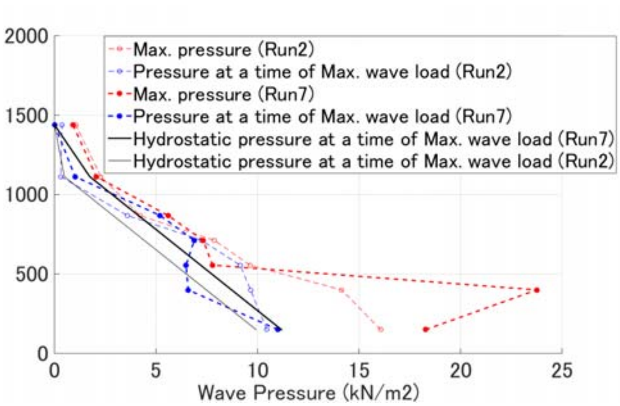
Fig. 6 – Water height and wave load relation in the hydro dynamic test

2.4 Wave Pressure Distribution

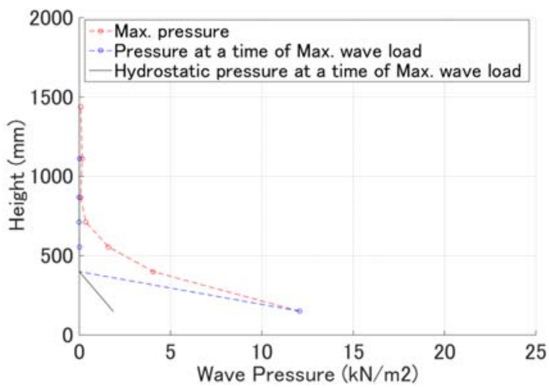
The vertical distribution of the wave pressure is shown in Fig.7. Two kinds of wave pressure (the maximum wave pressure and the wave pressure at the time of maximum wave load) are compared with the hydrostatic pressure of the water height at the time of maximum wave load. The maximum wave pressure indicates the maximum value at each measuring height, so that the plotted values were not obtained at same loading step. Local wave pressure exceeded the hydrostatic wave pressure at the time of maximum wave load. The wave pressure distribution is proportion to the height of measuring points and consistent with the water height at the time of maximum wave load. For S2 specimen, wave pressure on 2nd story above is negligible for the evaluation of the maximum wave load at RUN1.



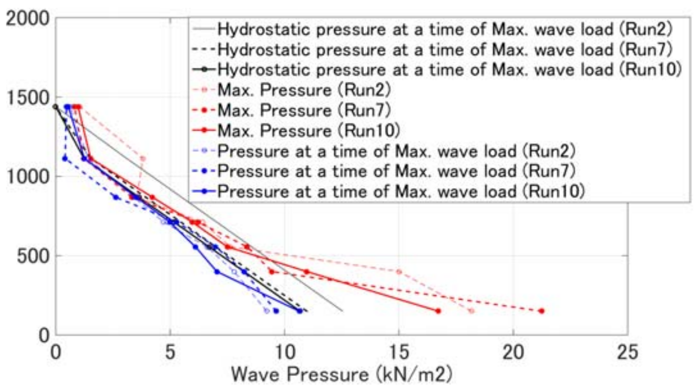
(a) S1A Specimen (RUN1&6)



(b) S1A Specimen (RUN2&7)



(c) S2 Specimen (RUN1)



(d) S2 Specimen (RUN2&7&10)

Fig. 7 – Wave pressure distribution in the hydro dynamic test

3. Static Loading Test

The static loading test has been carried out at the test laboratory in ERI after the hydro dynamic test as shown in Fig.8. For S1 specimens, the strength is calibrated with identical another specimen because two specimens collapsed in hydro dynamic tests. For S2 specimens, static loading test has been carried out with two specimens before and after the hydrodynamic tests in order to evaluate the maximum experienced story drift in the hydro dynamic test. The story drift of the specimen is measured at 335mm height from the base foundation by laser displacement meter. The lateral force is given at 535 mm height, which is one-third of the specimen height.

Fig. 8 – Static loading test of the specimen

The load displacement relation in the static loading test is shown in the Fig.9. The yielding strength of S1 specimen is 5 kN and the strength deterioration is not obvious in the test. This strength is smaller than the maximum strength of S1A specimen in the hydro dynamic test. It demonstrates the effect of strain velocity increases the strength of the specimen in the hydro dynamic test. On the other hand, the maximum strength of shaking test and static loading test is similar for S2 specimens. The strength deterioration is observed both in the shaking test and the static loading test. The hysteretic curve of two specimens approximate around 0.007 m story drift in negative direction, but the specimen without the hydro dynamic test shows higher strength. In this S2 specimen, the strength deterioration has been already occurred in the past hydro dynamic and shaking test, and the smaller strength has been recorded at the same story drift for damaged specimen.

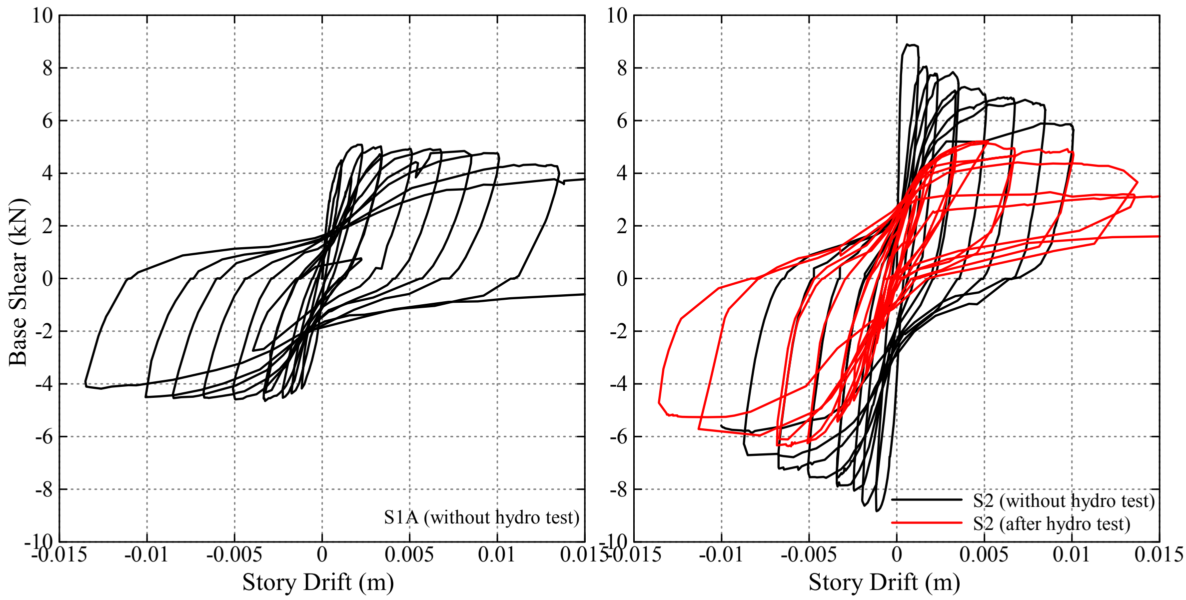


Fig. 9 – Load displacement relation in the static test

4. Concluding Remarks

The study shows the nonlinear response of the reinforced concrete soft first story specimens in hydraulic test, shaking test and static loading test. The following conclusions may be derived from these test results:

- It demonstrates the wave load causes the collapse of reinforced concrete structures due to the residual seismic damage by shaking, while it survives under the identical wave load without seismic damage.
- The maximum strength of the specimen in the hydraulic test is higher than those in the shaking test, the static loading test and the strength in calculation. It indicates the effect of strain velocity on the strength is prominent under the wave load.
- The wave load is smaller than the hydrostatic force evaluated with the water height when this value includes the afflux dammed by the specimen. This is because the wave pressure shows small value as approaching the side surface, and the integrated value of the wave pressure does not represents the hydrostatic force of water height in the central position of the specimen.
- The maximum wave pressure exceeded the hydrostatic wave pressure at a time of the maximum water height. The wave pressure at a time of the maximum wave load is proportion to the height of measuring points and consistent with the water height in front of the specimen.

5. Acknowledgements

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