TSUNAMI FORCE ON BRIDGE COMPARISON OF TWO WAVE TYPES BY EXPERIMENTAL TEST

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Abstract

Many bridges were washed away by tsunami due to Great East Japan Earthquake and it is significant to study how to evaluate wave force on bridge girder. The author firstly summarized that tsunami mainly shows steady flow shape, based on the video and photo recording tsunami along Kesen River. Besides, 1~3m waves are also found at surge front and water surface of steady flow. Afterwards, the experiments simulating bore wave and steady flow are conducted to study the characteristics of wave shape and horizontal wave forces on bridge girder. As a result, it is found that with same wave heights, wave force of broken bore wave is larger than un-broken bore wave and with similar inundation depths, the wave force of broken bore wave (prototype: inundation depth 20m, static water 7.5m, bore wave height 12.5m) is much greater than steady flow (prototype: inundation depth 17.5m).

Introduction

The 2011 Tohoku Earthquake, known as the Great East Japan Earthquake as well, occurred at 2:46 p.m. (JST) on March 11th 2011 with a magnitude 9.0. It was one of the most powerful earthquakes to have hit Japan. Besides that, the earthquake caused an extremely destructive tsunami which induced an extensive loss in Tohoku region. After the tsunami damage, the author carried out a reconnaissance visit to the coast of Rikuzentakata region and observed outflow condition of bridges. As illustrated in **Fig. 1**, in the tsunami affecting area drawn by Geospatial Information Authority of Japan, the 10 of 26 bridges across Kesen, Kawahara and Hamada Rivers were washed away and particularly all the three bridges across the widest Kesen River flowed out. Therefore the author tried to observe and draw the tsunami wave shape running along

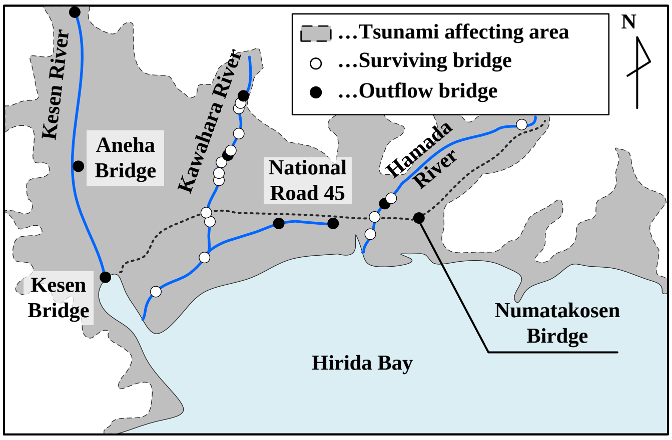

Fig.1 Tsunami Damage in Rikuzentakata Area

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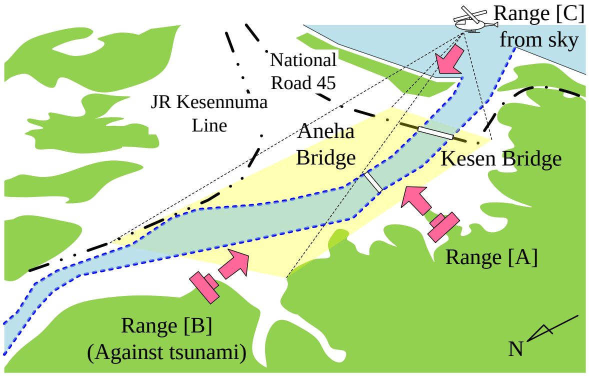


Fig.2 Photo or Video Ranges

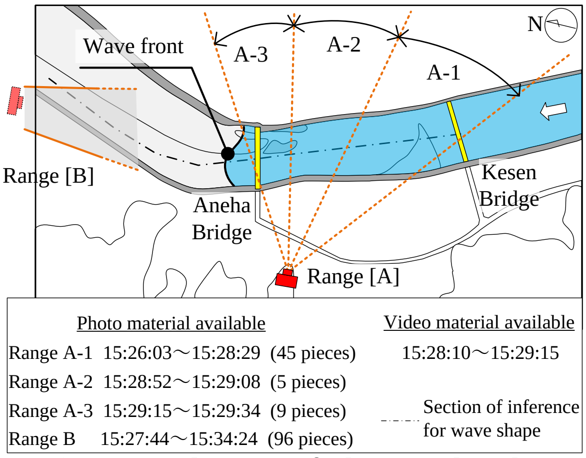


Fig.3 Introduction of Photo and Video Materials

Fig.4 Photo From Range A

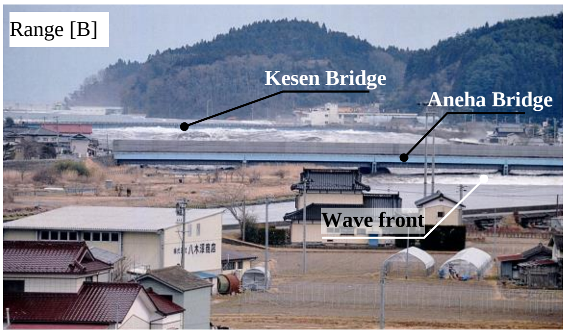


Fig.5 Photo From Range B

Kesen River by using the photos and videos recording tsunami.

During the field survey, the author collected the photos/videos recording tsunami along Kesen River. As shown in Fig. 2, three kinds of photos/video are used to draw wave shape. The photos of Range A were shot from upstream of Aneha Bridge and the photos of Range B were shot from the left bank of Kesen River. The video of Range C was shot by the Police of Iwate Prefecture in helicopter. The detailed camera angles and shooting time spans are given in **Fig. 3**. From Range A, the tsunami wave between Aneha and Kesen Bridge can be observed (**Fig. 4**) and the variation of wave height near Kesen Bridge can be estimated. From Range B, the tsunami surge front is able to be observed (**Fig. 5**), so the shape of surge front and the comparison of wave heights at Aneha and Kesen Bridges can be known. The shooting time of video from Range C is a little later than Range A and B. In the video, the surge front has passed Aneha Bridge (**Fig .6**). With the research of above photos and videos, the tsunami wave shape and flow velocity are evaluated.

Firstly, the flow velocity of surge front is estimated many times and it is computed by the ratio of flow distance and time span between two locations. As shown in **Fig. 7**, flow velocity is estimated at eight intervals ([1]~[2], [2]~[3], ···), and the ave. velocity is about 5~6m/s.

Fig.6 Video from Range C

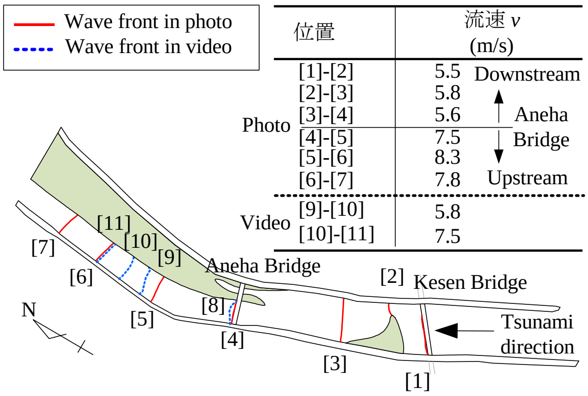


Fig.7 Wave Front and Velocity

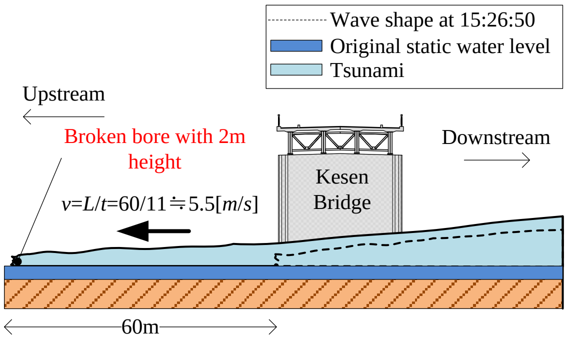


Fig.8 Shape of Wave Front

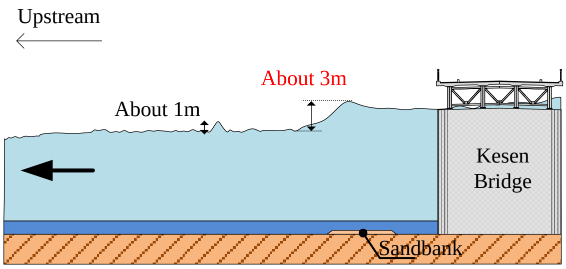


Fig.9 Wave Shape ahead of Kesen Bridge

Besides that, with the use of photos shot at Range A, the surge front of tsunami at location of Kesen Bridge is able to be drawn (**Fig. 8**). It is notable that the surge front kept the broken bore wave shape with 2m height. Besides, the flow velocity is estimated about 5.5m/s. As time went on, as plotted in **Fig .9**, when the water level reached to the bottom of Kesen Bridge, the 1m~3m small waves can be noted in front of Kesen Bridge and these waves were caused by the abrupt change of riverbed level. Further, the wave height at this time is estimated about 8.0m. With the method of wave shape estimation in **Fig. 8** and **Fig. 9**, the general wave shape from surge front to Kesen Bridge is able to be drawn roughly. As plotted in **Fig. 10**, the surge front just passed through Aneha Bridge with 2.0m height. On the other hand, the general wave shape from surge front to Kesen Bridge shows steady flow because the water surface gradient is computed as 1/85, which is a relatively small value. Therefore, according the observation of real tsunami, it is concluded that tsunami wave shows steady flow shape while the 1~3m small waves happens because of level change of riverbed.

Finally, the tsunami images from 15:28:23 to 15:30:52 before and after outflow of Kesen Bridge are illustrated in **Fig. 11**. It is obvious that the tsunami overflowed Kesen Bridge with a small speed, which was steady flow shape. By comparing the lamp positions at 15:29:36 and 15:30:52, it is known that due to the effect of steady flow, Kesen Bridge moved out gradually after submerging. From above survey, it is noted that the tsunami mainly shows steady flow shape, while 1m~3m waves happens on steady flow. Thus, in the following study, the experiments of steady flow and bore

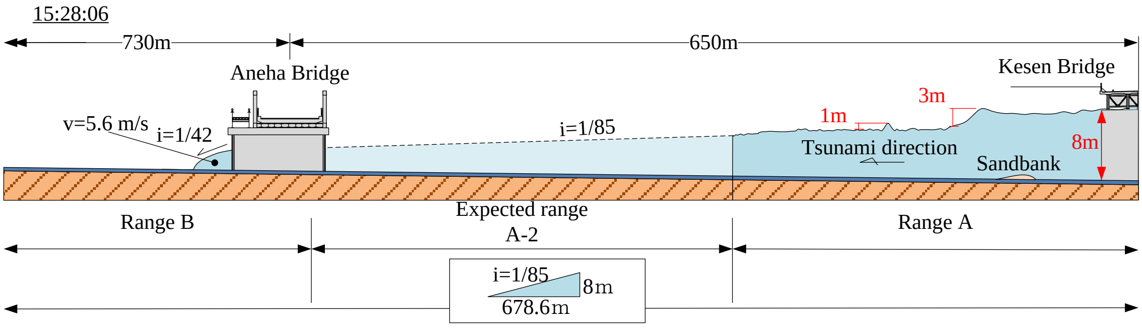


Fig.10 Wave Shape along Kesen River

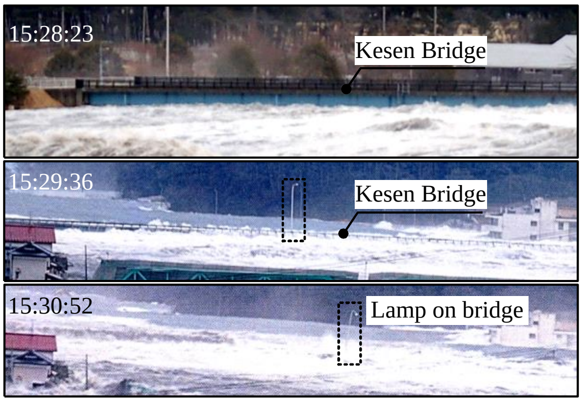


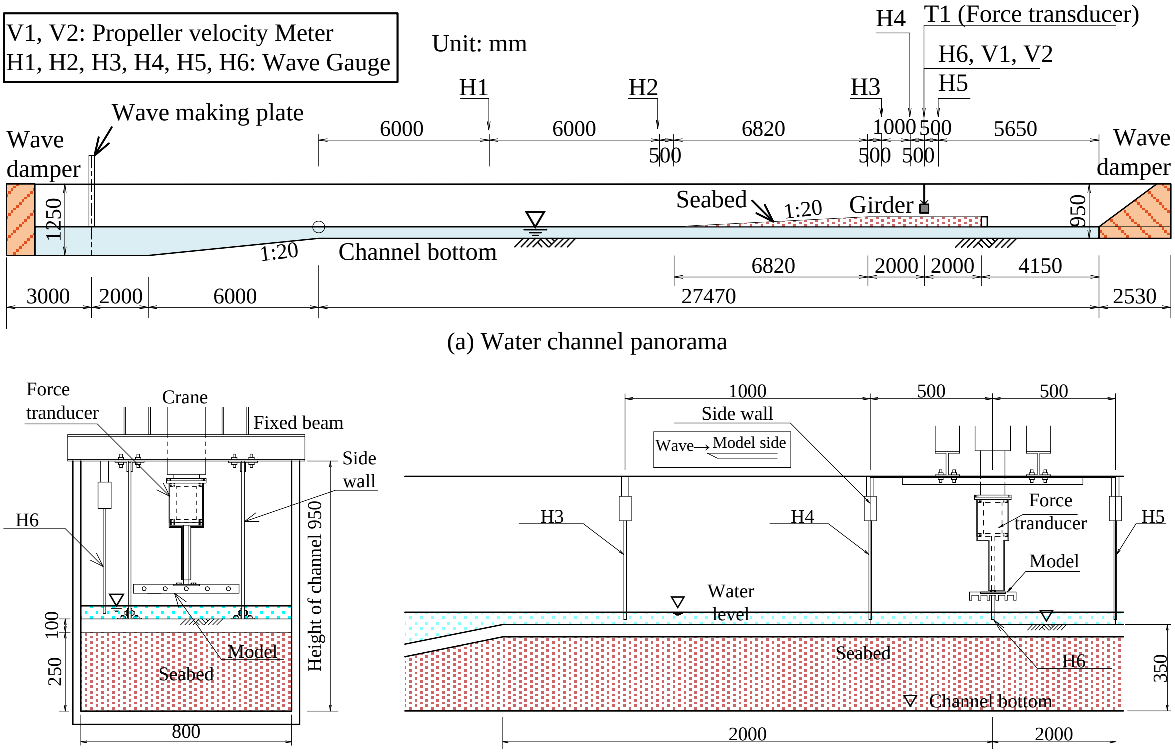
Fig.11 Wave Shape at the Moment that Kesen Birdge Flowed out

wave are conducted to research the characteristics of wave forces on girder.

Measurement of Bore Wave

In this chapter, the facilities for bore wave experiment are introduced. As illustrated in **Fig. 12-(a)**, the 41m-long, 80cm-wide, 125cm-high water channel is used for experiment. At the left side of channel, a vertical wave making plate is controlled by computer to create sine bore wave (input static water depth and wave height into computer). From the command of computer, the wave with target height is able to be created. At the location of bridge girder model, a seabed is set up to simulate seabed terrain. The model is located at the middle of horizontal plane.

The facilities near model are shown in **Fig. 12-(b)** and **Fig 12-(c)**. As the characteristic of experiment, two side walls are installed to be close to the ends of model. Six wave gauges are set up along the water channel. H1 and H2 are used to check the difference between creating wave height and input wave height. H3 and H4 are applied to check the variation of wave height due to effect of seabed. H5 is used to get the variation of wave height after the wave impacts on model. H6, at the outside of side wall, is set at the location of model to measure the wave height acting on model. Since being at the outside of side wall, the measurement of H6 is not influenced by the wave turbulence caused by the impact of wave and model. The force transducer, the range of which is 0~980N, can measure the wave horizontal force (called wave force in the following content), uplift force and acting moment caused by wave force on girder.



(a) Water channel panorama

(b) Front view

(c) Side view

Fig.12 Facility Condition (Bore Wave, Unit: mm)

Before experiment, the natural frequency of force transducer is confirmed as 30Hz while the intervals of output data of all facilities is 1/1000s.

The prototype of bridge girder model is the damaged Lueng Ie Bridge at Sumatra of Indonesia, due to Indian Ocean Tsunami. With the scale of 1/50, the length, width and height of model are made by 40cm, 19cm and 3.4cm respectively (prototype: 19.1m-long, 10.2m-wide and 1.7m-high).

Evaluation for Bore Wave

Fig. 13 plots the parameters of experiment for bore wave. Three kinds of parameters are mainly considered: ① wave height (a); ② model position (Z: height from static water level to model bottom); ③ bore wave shapes (broken wave and un-broken wave). With the model scale 1/50, based on the Froude similarity law, the wave height and girder position in standard case is set as 25cm and 4.8cm (wave height mentioned in the following content refers to the wave height measured by H6). Referring that the ave. wave height of tsunami attacking East Japan was 10~20m, so the 12.5m-high bore wave is simulated in standard case. And considering the girder height of the damaged bridges in East Japan from ground level is about 10m, the model position 2.4m (10m minus static water depth 7.5m) is simulated in standard case. After that, three patterns of experimental cases are set by changing parameters. In Pattern 1, the wave height is 25cm, and the model position Z is changed with 1cm pitch from -4cm to 18cm (Z=4.8cm included). The creating wave becomes broken wave when acting on model. In Pattern 2, the wave height is 11cm, and the model position Z is

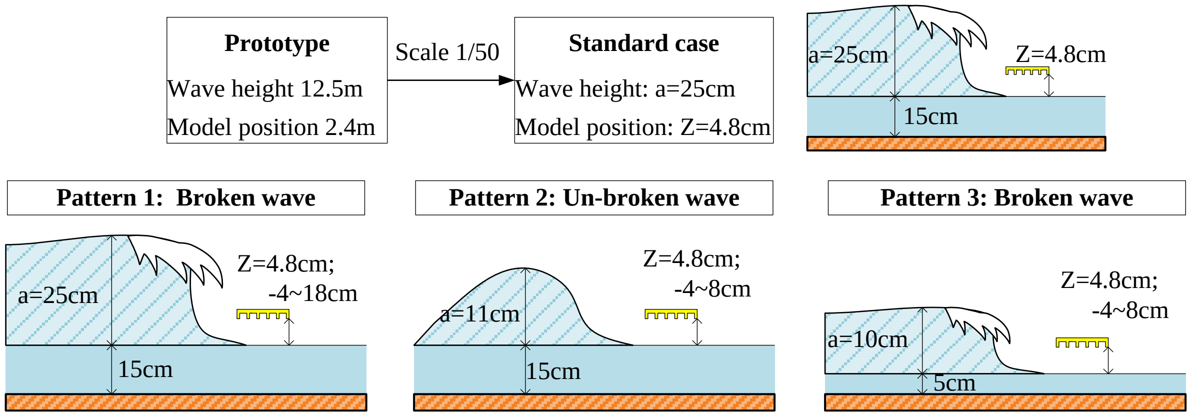


Fig.13 Parameters of Bore Wave Experiment

changed from -4cm to 8cm with 1cm pitch (Z=4.8cm included). The creating wave keeps mountain shape of un-broken wave when acting on model. In Pattern 3, the wave height is 10 cm, which is close to Pattern 2, and the model position Z is changed from -4cm to 8cm with 1cm pitch (Z=4.8cm included). But different from Pattern 2, the creating wave becomes broken wave when acting on model. In summary, the three patterns of cases are presented by: Pattern 1 [h=15cm, a=25cm, broken wave]; Pattern 2 [h=15cm, a=11cm, un-broken wave]; Pattern 3 [h=5cm, a=10cm, broken wave]. From the study of pattern 1 and 3, the relationship between wave force and wave height can be studied. From the comparison of Pattern 2 and 3, the difference of wave forces between broken and un-broken waves can be understood.

In the experiment, the max. wave force on model is concentrated. As plotted in **Fig. 14**, it is introduced as the representative result of wave force. It is known that the vibration period of 1/1000s output is about 0.033s (frequency: 30.3Hz). As mentioned in previous chapter, the natural frequency of force transducer is 30Hz, so it is considered that the resonance occurs in the result of 1/1000s time interval. In order to eliminate the resonance effect, the output by moving average of 1/10s time interval (called 1/10s average in the following content of this chapter) is also plotted. After conducting 1/10s average, the vibration larger than 5Hz is eliminated. And it is known that the max. wave force decreases about 20% (from 23.8N to 19.6N). The result of 1/10s average is used for evaluation of wave force. Besides, in order to ensure the reappearance of experiment, each case is conducted by three times.

Afterwards, as an example of broken wave, the result of standard case (Pattern 1, a=25cm, Z=4.8cm, broken wave) is introduced. **Fig. 15** is outlined based on the video recording experiment. It is notable that when wave is acting on girder, the white spray jumps on model top and then the wave block (blue color) without white spray moves to girder from lower left. In summary, the broken wave is the combination of white spray and blue water block, and the white spray mainly acts on girder.

In **Fig .16**, the relationship between wave height and wave force of standard case is illustrated. The wave height does not display the regular sine shape, which means the original sine wave deforms to broken wave at girder location. The peak

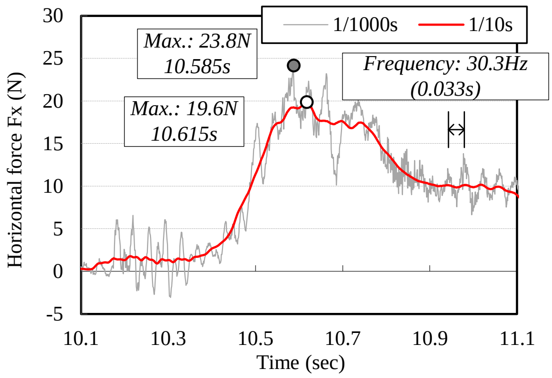


Fig.14 Evaluation Method of Bore Wave (a=10cm, Broken Wave, Z=4.8cm)

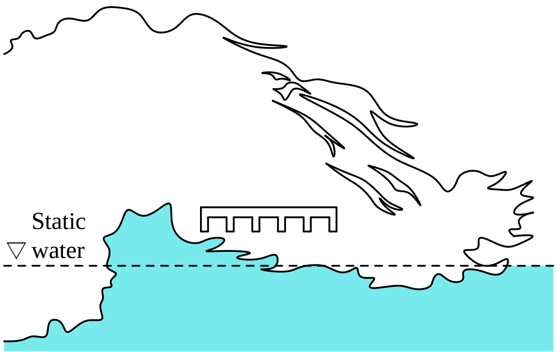


Fig.15 Wave Shape of Broken Wave (Standard Case)

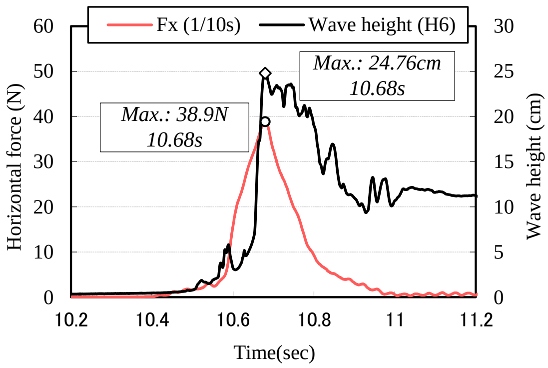


Fig.16 Wave Height and Wave Force (Standard Case)

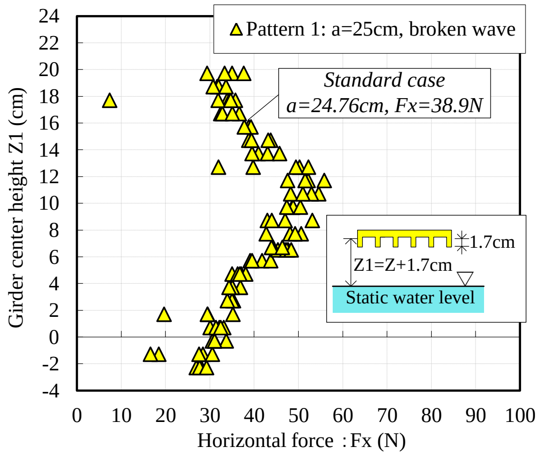


Fig.17 Wave Force Distribution (Pattern 1)

height 24.8cm is recorded at 10.68s. The max. wave force, which is 38.9N happens at the same time while the peak wave height occurs. The wave height and force change with the similar trend. Afterwards, in **Fig. 17**, the max. wave forces of each case of Pattern 1 are extracted. Considering the wave force mainly acting on model front surface, the vertical coordinate is defined by model center height Z1 (=Z+1.7cm) from static water level to model center. When the model position is fixed at the half of wave height (Z=12cm), the max. wave force occurs. When the model position is fixed at the static water surface (Z=0cm) and close to wave crest (Z=18cm), the wave force decreases to half of the max. force. So in the condition of broken wave, the model position is a significant parameter affecting wave force.

Next, to un-broken wave of Pattern 2, the result of a representative case (a=11cm, Z=4.8cm) would be described. The procedure that wave acts on model is plotted in **Fig. 18**. The blue wave water block acts on girder and keeps mountain shape. Compared with broken wave in **Fig. 15**, it is obvious that different from broken wave, there is no large amount of white sprays produced.

In **Fig. 19**, the relationship between wave height and wave force of the case in

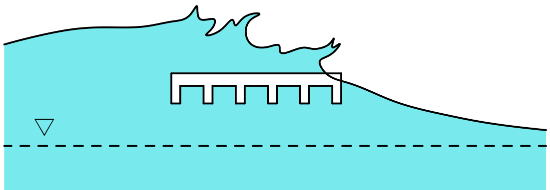


Fig.18 Wave Shape of Un-broken Wave (Pattern 2, Z=4.8cm)

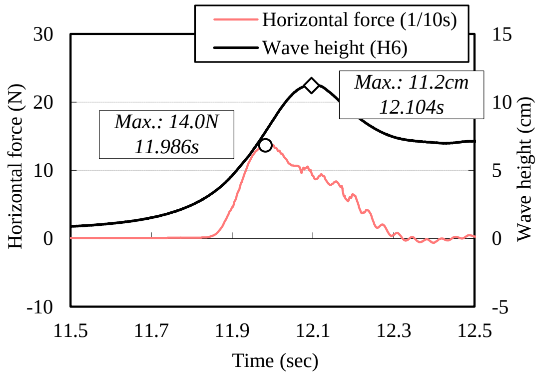


Fig.19 Wave Height and Wave Force (Standard Case)

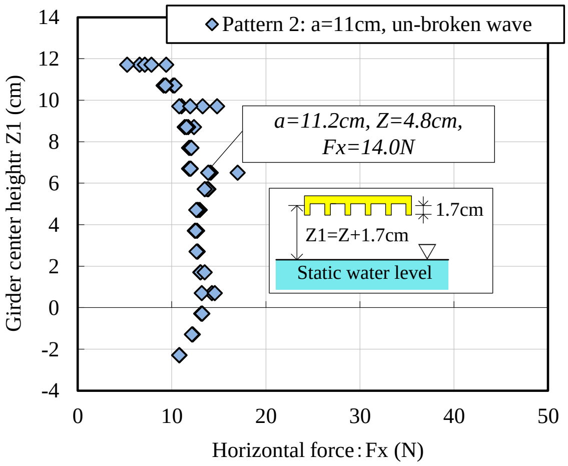


Fig.20 Wave Force Distribution (Pattern 3)

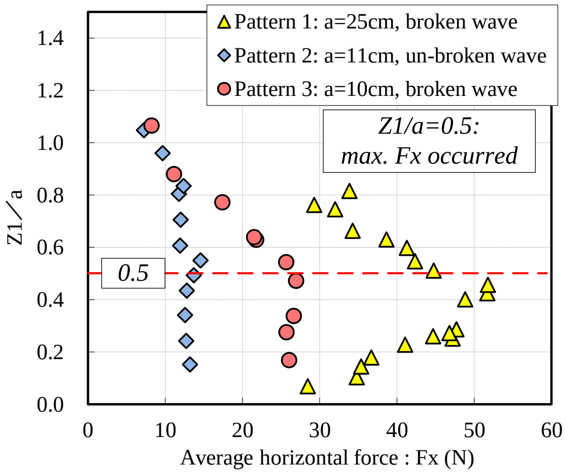


Fig.21 Wave Force Distribution (Ave.)

Fig. 18 is illustrated. The wave height result is a smooth curve, which is like a mountain shape. The peak height happens at about 12.1s. Although the variations of wave height and wave force show same trend, the max. force 14.0N happens a little earlier than peak wave height. Afterwards, in **Fig. 20**, the max. wave forces of all cases of Pattern 2 are extracted, with vertical coordinate as model center height Z1. It is found that the wave forces almost present a constant 13N for the cases with model position of Z=0~10cm and this trend is different from the distribution of wave forces by broken wave in Fig. 17 that whatever Z1/a<0.5 or Z1/a>0.5, the wave forces decrease fast.

On the basis that the representative cases of broken and un-broken waves have been introduced, the wave force of cases of all three patterns are put together for comparison (ave. wave force of three times of repeated measurements are used). As shown in **Fig. 21**, for comparison of three patterns, the vertical coordinate is conducted by dimensionless value Z1/a. Considering that real bridges are set above static water level, the cases that model under static water level (Z1<0) are ignored. Firstly, it is obvious that generally the wave forces of Pattern 3 present greatest level, and it is considered as main reason that the wave height of Pattern 1 is greatest. Secondly,

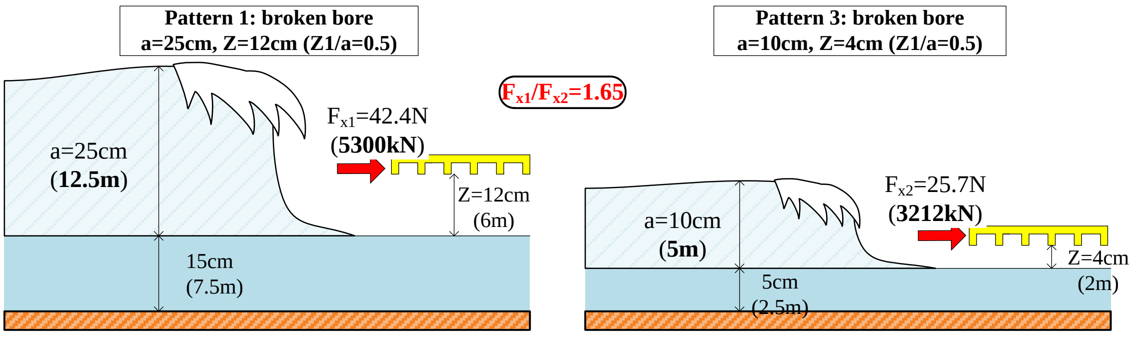


Fig.22 Wave Shape of Un-broken Wave (Pattern 2, Z=4.8cm)

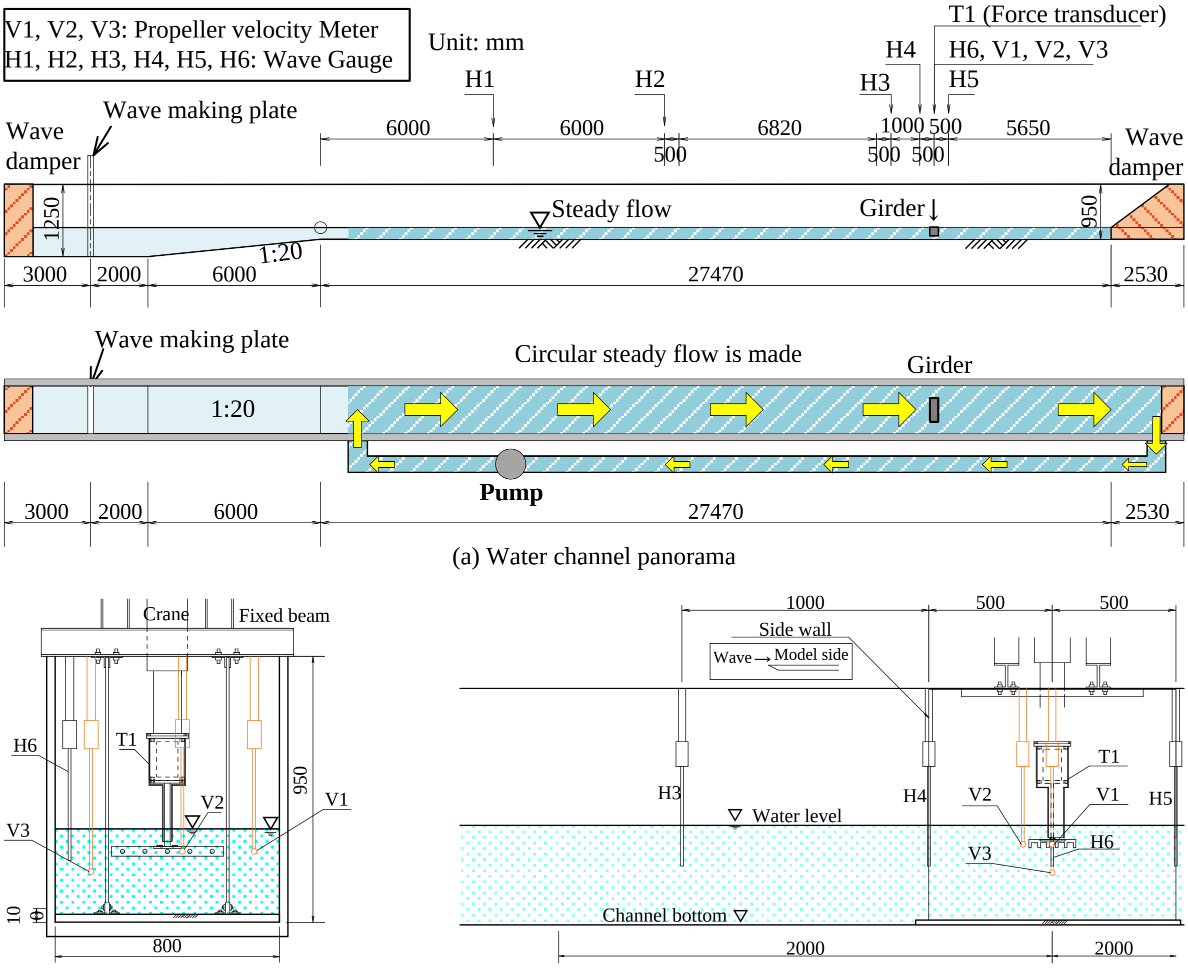
although the wave height of Pattern 2 is slightly larger than Pattern 3, the wave force of Pattern 2 is smaller than Pattern 3. Therefore, it is considered that with same wave height, the wave force of broken wave is stronger than un-broken wave. Furthermore, the common point of three patterns is found that the max. forces always happens when the model central height Z1 is set at half of wave height (Z1/a=0.5).

After that in order to understand the wave force difference between 12.5m-high and 5.0m-high bore wave, the two representative cases with max. forces of Pattern 1 and 3 are selected, and besides, the experimental wave forces are converted to conditions of prototypes based on Froude similarity law. As a result, the max. wave forces of 12.5m-high and 5.0m-high bore waves are 5300kN and 3212kN, namely the max. wave force of 12.5m broken wave is about 1.65 times larger than the max. wave force of 5.0m-high broken wave (F_{x1}/F_{x2}=1.65,). Therefore, the larger wave height would cause greater wave force and the wave height should be considered as a significant parameter for evaluation of max. wave force of bore wave.

Measurement of Steady Flow

The experiment of steady flow has also been carried out. As shown in **Fig. 23-(a)**, the same water channel and girder model as bore wave are used. But different from bore wave experiment, the pump installed on water channel is applied to make a steady circular flow. The circular length is about 30m and the circular flow velocity is able to be controlled by the rotation speed of pump. In order to ensure the stability of steady flow, the seabed in bore wave experiment is removed. The max. flow velocity 120cm/s (8.5m/s) can be created. With the adjustment of crane (**Fig. 23-(b)**), the model can be put down into steady flow to measure wave force. The measurement by H6 at outside of side wall is applied to evaluate the steady flow depth at model location.

In the steady flow experiment, the author considered flow velocity is the significant parameter for wave force evaluation, and proposed the method of measuring flow velocity. Three propeller velocity meters are applied to measure flow velocity of steady flow. In the ideal steady flow condition, the average flow velocity happens near the central flow depth, thus the velocity meter V3 is set at the central depth of steady flow to manage the average flow velocity. Moreover, the velocity meters V1 and V2 are set at the same depth as model to measure the flow velocity that acts on model. V1 is set



(a) Water channel panorama

(b) Front view (c) Side view

Fig.23 Facility Condition (Steady flow, Unit: mm)

at outside of side wall while V2 is set right ahead of model (5cm far away from model front). Considering the measurement of V2 is affected due to the impact of flow and girder, V1 is used to evaluate flow velocity that acts on girder.

Evaluation for Steady Flow

In steady flow experiment, three types of parameters were considered: steady flow depth, flow velocity and model center height in steady flow. The steady flow depth and velocity of experiment are set based on the conditions of tsunami happened in Tohoku area. From the videos and photos that record tsunami conditions of Utatsu area, Koizumi area and Rikuzentakata area, it is known that the flow depth is between 10~20m, and the average flow velocity is about 6.0m/s[1)]. Therefore, the 35cm flow depth (17.5m) and 75cm/s flow velocity (5.5m/s) are set in the standard case (**Fig. 24**). And the Froude number Fr of standard case is calculated as 0.40. Besides, considering that the most stable flow condition happens in the middle depth, model center is set as Z1=14cm in standard case. Afterwards, another two types of flow velocities 50cm/s (3.5m/s) and 100cm/s (7.1m/s) are supplied flow velocity parameters. Furthermore, in order to understand the flow velocity and wave force variations in vertical direction, for

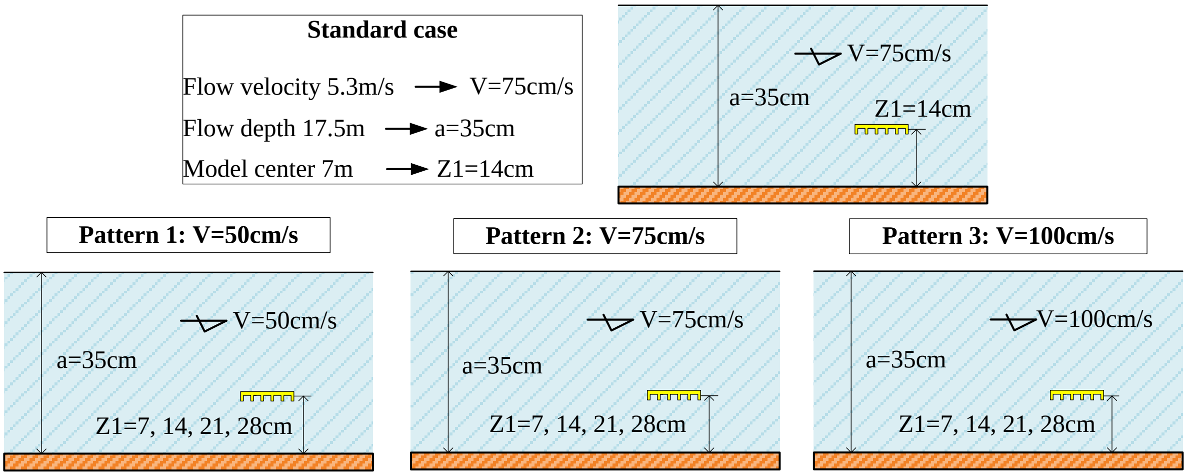


Fig.24 Parameters of Steady Flow Experiment

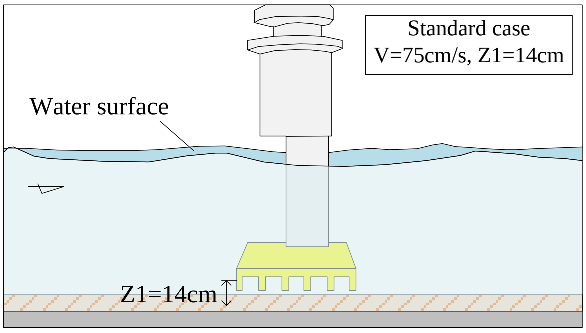


Fig.25 Shape of Steady Flow

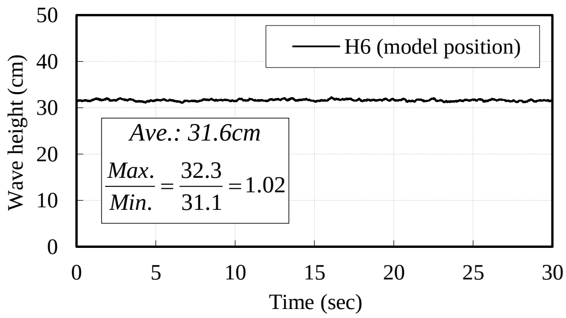


Fig.26 Wave Height (Standard Case)

each pattern of velocity parameter, the model central height in steady flow is set as another parameter (Z1=7, 14, 21, 28cm). Each case is conducted by three times to ensure the reasonability of measurement.

Above all, the experimental result of standard case is introduced. As shown in **Fig. 25**, drawn based on the video recording experiment, the flow condition of steady flow can be observed. It is notable that the water surface only shows small up-and-down motion, which is similar to the real tsunami condition in **Fig. 11**. Before creating steady flow, the static water depth is set as 35cm. Then the 35cm static water is driven by pump to make steady flow. From the wave height measurement (output interval: 1/1000s) by wave gauge H6 in **Fig. 26**, it is known that the flow depth at model became 31.6cm because a very small gradient happens on water surface after creation of steady flow by referring to the measurements by H1 (left end of steady flow, ave.: 34.5cm) and H6 (right end of steady flow, ave.: 31.6cm). Besides, the steady flow keeps stable condition approximately, because the difference between max. and min. wave height is only 2%.

With the management by velocity meter V3, the flow velocity in middle depth is adjusted as about 75cm/s. The flow velocity result by V1 is illustrated in **Fig. 27**. Different from wave height, the output of 1/1000s time interval generates great

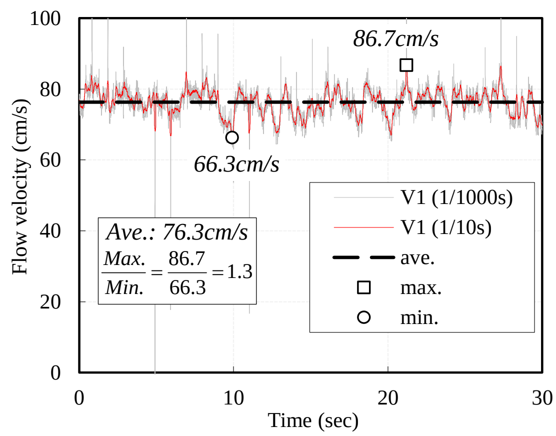


Fig.27 Steady Flow Velocity by V1 (Standard Case)

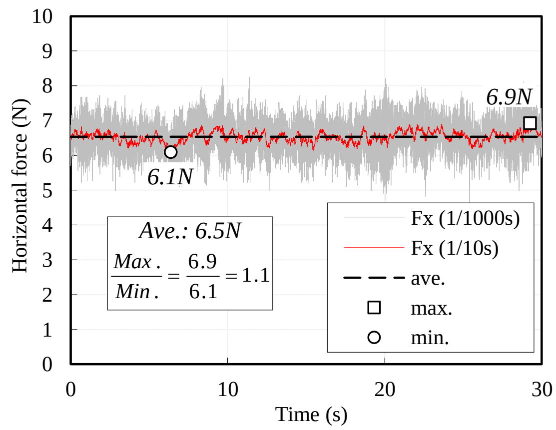


Fig.28 Wave Force (Standard Case)

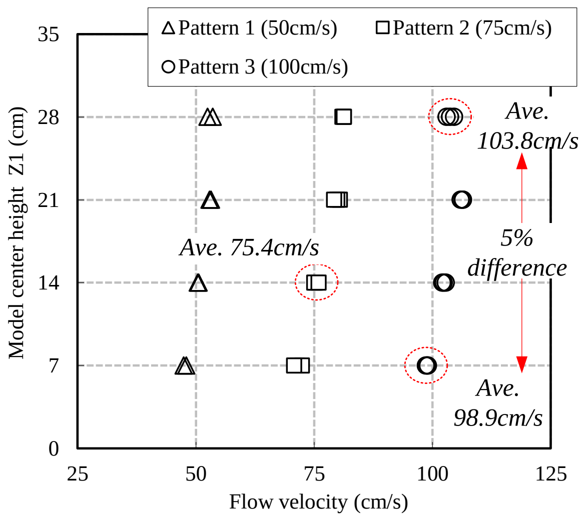


Fig.29 Flow Velocity Distribution (V1)

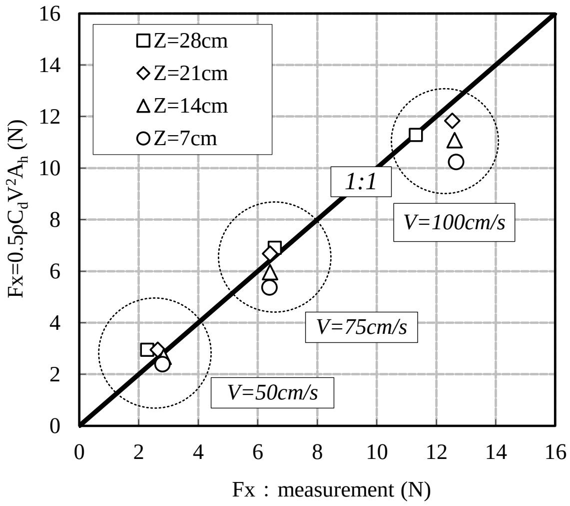


Fig.30 Comparison of calculating and measuring wave forces

vibration due to the electromagnetic noise. Therefore, the output by moving average of 1/10s time interval (called 1/10s average in the following content of this chapter) is applied to eliminate the vibration caused by electromagnetic noise. Although the difference between max. and min. flow velocities is about 30%, the average velocity after 1/10s moving average is 76.3cm/s, which is close to the objective 75cm/s and the 1/10s result 76.3cm/s is used for evaluation.

After that, the wave force is given in **Fig. 28**. Similar to velocity, the output of 1/1000s time interval is disturbed by electromagnetic noise, so the result of 1/10s average is applied for evaluation. From result of 1/10s average, it is obtained that the difference between max. and min. wave forces is 10% and both the max. and min. wave forces are close to ave. value, so the ave. wave force 6.5N can be used for evaluation.

By the same evaluation method of flow velocity as **Fig. 27**, the ave. velocity of

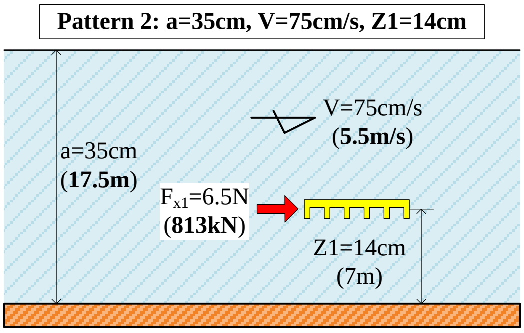


Fig.31 Wave Force of Prototype of Steady Flow

other cases are obtained. In **Fig. 29**, the flow velocities of all cases (including results of repeated measurements) are plotted. For each case, the deviation of repeated measurements is minor, so the reappearance of velocity measurement is good. For all the three patterns, from flow surface to bottom, the velocity decreases slightly. For example, to Pattern 3 (the greatest 7.1m/s steady flow is simulated), the ave. velocity from flow surface to bottom only decreases 5%. Therefore, the stable steady flow condition can be confirmed. After that, according to the research[2)], it is known that the wave force is mainly correlated with flow velocity and is able to be evaluated by the following Eq. (2), in which, wave force is the function of flow velocity and drag coefficient:

$$Fx = \frac{1}{2}\rho_w C_d v^2 A_h \tag{2}$$

Where, Fx is the wave force (kN); ρ_w is the sea water density (1.03g/cm^3); C_d is the drag coefficient (1.54, calculated by the Japanese Specification[3)]); v is the tsunami velocity (m/s); A_h is the effective projected area on girder (m^2).

For steady flow condition, the reasonability of Eq. (2) can be checked based on the experimental result. The calculation of wave force by standard case is shown as an example. By substituting the average flow velocity measured by three times with V1 (76.3cm/s in **Fig. 27**), into Eq. (2), the wave force is able to be calculated as 6.0N. On the other hand, the wave force is measured as 6.5N (**Fig. 28**), so the difference between calculation and measurement is 7%. Furthermore, the wave forces of all other cases are also calculated and the comparison between calculation and measurement is illustrated in **Fig. 30**. As a consequence, it is apparent that the calculation and measurement show the same level for all three patterns. In summary, the wave force of steady flow is proportional to the square of flow velocity and has no relationship with flow depth.

By converting the standard case “a=35cm, V=75cm/s, Z=14cm” to bridge prototype, as shown in **Fig. 31**, the 5.5m/s (ave. tsunami flow velocity in Tohoku region) steady flow with 17.5m tsunami inundation depth causes 813kN force on girder. After that, the difference of wave force between bore wave and steady flow with similar tsunami inundation depths can be understood by comparing **Fig. 31** and **Fig. 22**. As mentioned in **Fig. 22**, by converting the case “h=15cm, a=25cm, Z=12cm” to prototype , it is known that, with 20m inundation depth, the 12.5m broken bore wave causes 5300kN force on girder at most. Therefore, with similar inundation depths (broken wave: h+a=20m, steady flow: 17.5m), the wave force of 12.5m broken wave is about 6.5 times greater than the wave force caused by 17.5m steady flow (5.5m/s), which is a big difference. Thus, in the condition of tsunami with 10~20m inundation depth, if design wave force on basis of bore wave, the wave force may be overestimated.

Conclusions

From the photo/video analyses and experimental tests of bore wave and steady flow, the following conclusions are summarized:

(1) From the video and photo recording tsunami along Kesen River, it is concluded that the tsunami long wave shows steady flow shape generally. Besides, 1~3m small waves can be found at the surge front and water surface of steady flow.

(2) By the experiment of broken and un-broken wave, it is summarized that with the same heights, the max. wave force of broken wave is about twice greater than un-broken wave. Besides, the max. wave force of bore wave occurs when model position is set at the half of wave height (Z1/a=0.5).

(3) From steady flow experimental result, both the flow velocity and wave force almost do not change for different girder model positions. From the comparison of calculated and measured wave forces, it is found that the wave force is proportional to the square of flow velocity.

(4) If converting broken wave case “h=15cm, a=25cm, Z=12cm” to prototype, it is known that the 12.5m broken wave causes 5300kN force on girder at most. If converting steady flow case “a=35cm, V=75cm/s, Z=14cm” to prototype, it is found that the steady flow (17.5m, 5.5m/s) causes 813kN force on girder. Thus, it is concluded that although with similar inundation depths (broken wave: 20m, steady flow: 17.5m), the max. wave force of broken bore wave is about 6.5 times greater than the wave force of steady flow.

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