17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

BENCHMARK PROBLEMS FOR ANTI-TSUNAMI DESIGN OF BRIDGES

K. Izuno[(1)], K. Kosa[(2)]

[(1)] *Professor, Ritsumeikan University, izuno@se.ritsumei.ac.jp*
[(2)] *Professor Emeritus, Kyushu Institute of Technology, kosakenji@yahoo.co.jp*

Abstract

Understanding the forces exerted on bridges by tsunamis has become an important issue in Japan following the 2011 Great East Japan earthquake and tsunami. During that event, several bridges were damaged by the tsunami that followed in the wake of the earthquake. When bridges are washed away by a tsunami, valuable social capital is lost and there may be delays in rescuing people and supplying goods to affected areas. Therefore, measures must be taken to protect bridges from tsunamis. Recently, many studies have examined the impact of tsunamis on bridges. However, a standard anti-tsunami design method for bridges has not yet been established.

The subcommittee on anti-tsunami design methods for bridges was formed in 2015 as a part of the earthquake engineering committee of the Japan Society of Civil Engineers (JSCE) to discuss problems concerning the anti-tsunami design of bridges. The subcommittee also aims to share information about this issue with JSCE members. This paper reports the outcome of the symposium on benchmark problems affecting the anti-tsunami design of bridges. The aim of this report is to share information relating to numerical analysis of methods in this research field.

The subcomittee provided 2 cases for the benchmark tests : Case 1 was solitary wave problem and Case 2 was dam break problem.

The results of the analysis of Case 1 have already been published, so the participants were able to evaluate the accuracy of their results by comparing them with the published results. The results are summarized as follows: a) All participants calculated horizontal forces generally corresponding to the test results. However, all of them overestimated the impact force when the wave first arrived at the model. b) The estimation of the vertical force was less accurate than that of the horizontal force.

Case 2 was provided to discuss the effects of tsunami induced forces on a skewed bridge. The results of Case 2 had not been published prior to the symposium so this was the first time this problem could be evaluated. The results are summarized as follows: a) All participants calculated horizontal transverse forces perpendicular to the bridge axis at 85%-150% of the experimental result, which was accurate enough to be used as an estimate tsunami force for the bridge anti-tsunami design. b) The estimation of the vertical force was less accurate than that of the horizontal transverse force. The percent difference between the estimate and the experimental results was 50%-200%. The separating wave at the edge of the bridge model, which was very difficult to simulate accurately, affected much on the vertical force.

Keywords: tsunami, bridge, numerical simulation, benchmark problems

1. Introduction

Understanding the forces exerted on bridges by tsunamis has become an important issue in Japan following the 2011 Great East Japan earthquake and tsunami. During that event, several bridges were damaged by the tsunami that followed in the wake of the earthquake. When bridges are washed away by a tsunami, valuable social capital is lost and there may be delays in rescuing people and supplying goods to affected areas. Therefore, measures must be taken to protect bridges from tsunamis. Recently, many studies have examined the impact of tsunamis on bridges [1-12]. However, a standard anti-tsunami de-sign method for bridges has not yet been established.

The subcommittee on anti-tsunami design meth-ods for bridges was formed in 2015 as a part of the earthquake engineering committee of the Japan So-ciety of Civil Engineers (JSCE) to discuss problems concerning the anti-tsunami design of bridges. The subcommittee also aims to share information about this issue with JSCE members. The subcommittee consists of 22 members whose major research areas include earthquake engineering, structural engi-neering, applied mechanics, hydraulics, and coastal engineering. The subcommittee will be in place until 2017 and will publish guidelines for the anti-tsunami design of bridges.

This paper reports the outcome of the symposium on benchmark problems affecting the anti-tsunami design of bridges, which was held on August 4, 2016 in Tokyo, Japan. About 50 participants dis-cussed various issues concerning numerical methods for determining the effects of tsunamis on bridge structures. The aim of this report is to share infor-mation relating to numerical analysis of methods in this research field.

2. Benchmark problems

The subcommittee examined two benchmark problems. The experimental results of Case 1 were already published prior to the symposium, while the results of Case 2 were not disclosed until the symposium. We allowed symposium participants to access information on the experiments, and the participants used various numerical methods to calculate the forces induced by tsunamis on structures.

2.1 Case 1: solitary wave problem

The problem presented in Case 1 was chosen from experiments conducted at Kyushu Institute of Technology. The results of the analysis of Case 1 have already been published [13, 14], so the participants were able to evaluate the accuracy of their results by comparing them with the published results. Case 1 was provided to allow participants to discuss the methodology and to discuss how to get accurate results.

Fig. 1 shows a hydraulic experiment channel and Fig. 2 shows a bridge girder model. The initial water height was 35 cm, and the center of the model was set to 10 cm above the initial water height. Then, a solitary wave 20 cm high was generated, which caused drag and lift forces to be exerted on the model. The wave-making device was a slide type board controlled by the computer. The necessary force to push the wave-making board was determined from the required wave height and the initial water depth.

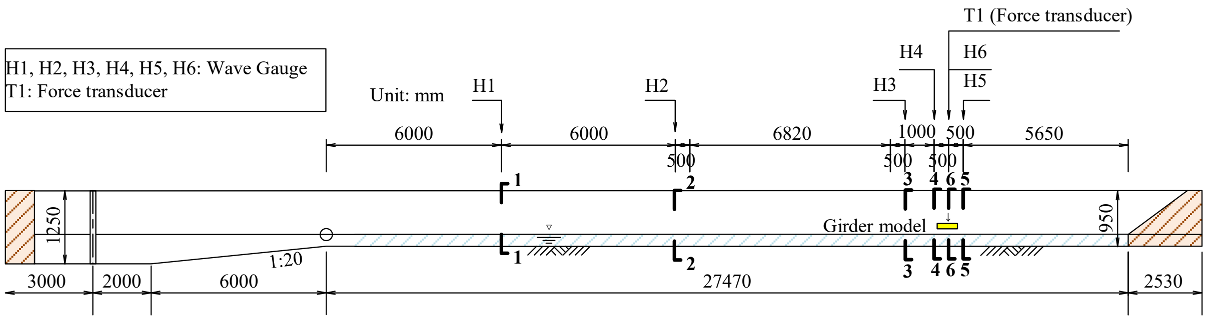


Fig. 1 – Hydraulic experiment channel used in Case 1

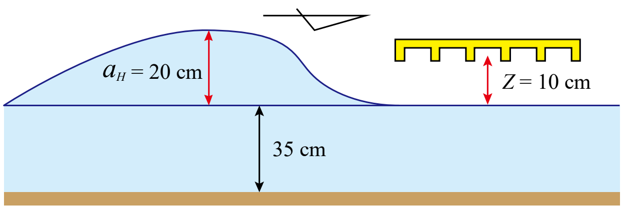


Fig. 2 – Bridge girder model used in Case 1

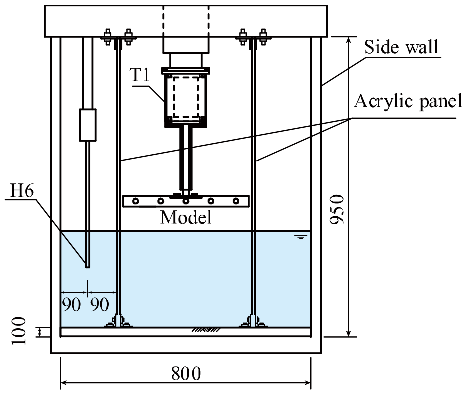


Fig. 3 – Setup of load transducer in Case 1

Fig. 3 shows the setup of the load transducer to measure the horizontal and vertical forces acting on the bridge model. A vertical rigid beam was fixed to the bridge model and connected to the upper part of the tank. The load transducer (T1 in Fig. 3) was installed on the vertical beam. The height and velocity of the wave were also measured. These results were available digitally on the subcommittee website.

2.2 Case 2: skewed bridge

Case 2 was provided to allow participants to discuss the effects of tsunami induced forces on a skewed bridge. The results of Case 2 had not been published prior to the symposium so this was the first time this problem could be evaluated. The experiments were conducted at Ritsumeikan University using a skewed prismatic model and a rectangular parallelepiped model without skew.

The participants were requested to estimate the transverse horizontal force applied perpendicular to the skewed bridge model, the longitudinal horizontal force applied along the model, and the vertical (lift) force applied to the model. They could use the water height and velocity data obtained from the experiment, and could refer the tsunami induced forces to the model without skew under the same conditions.

The experimental channel shown in Fig. 4 was used for the hydraulic experiments. The open channel was 200 mm wide and 3,400 mm long, and it was attached to a tank that was 200 mm wide and 2,000 mm long. The water tank was filled with water to simulate tsunami flow in an open channel. A gate was installed between the channel and the tank, which could be abruptly removed to generate a wave similar in form to a tsunami.

The bridge model was located 2,500 mm downstream from the gate and 40 mm above the channel bottom. The bridge model without skew was a 100 × 20 × 190 mm rectangular parallelepiped, and the model with skew had the same projected area in three directions parallel to the axes with a skew angle of 60°, as shown in Fig. 5.

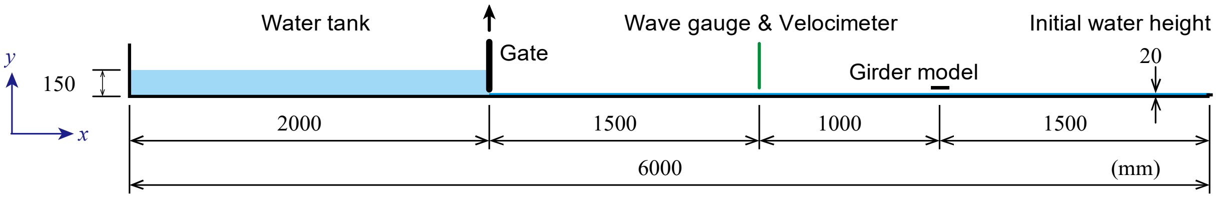
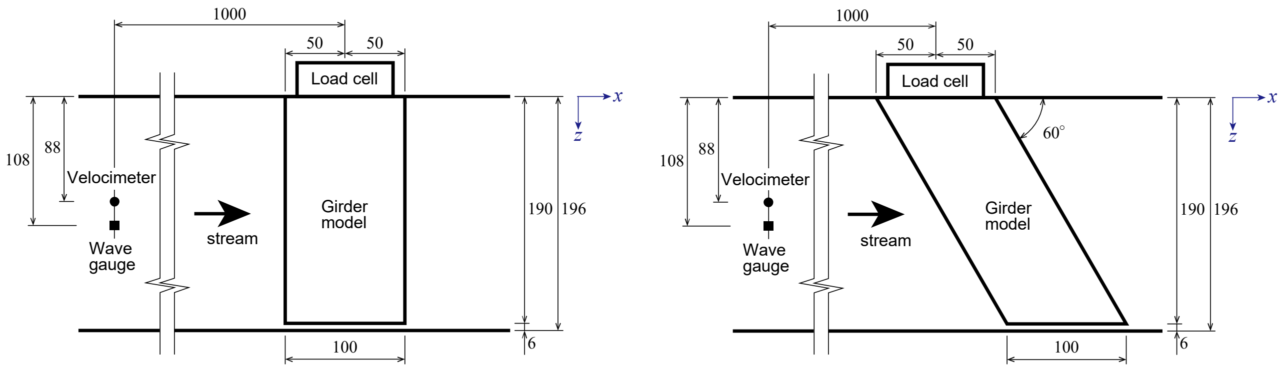


Fig. 4 – Hydraulic experiment channel used in Case 2



(a) Straight bridge model (b) Skewed bridge model

Fig. 5 – Bridge girder models used in Case 2

The bridge model was supported by the device that was connected to the load cell. The three-component load cell measured and recorded transverse, longitudinal, and vertical tsunami forces at a sampling rate of 100 Hz.

3. Results and discussions

3.1 Case 1: solitary wave problem

Seven participants used computational fluid dynamics (CFD) software, as shown in Table 1.

Table 1 – Software used in Case 1

	Software
No. 1	CADMAS-SURF/3D [15] modeled in 2D, mesh size = 1 - 10 mm
No. 2	CADMAS-SURF/3D [15] mesh size = 5 - 25 mm
No. 3	SPH DualSPHysics [16] modeled in 2D, number of particles = 500,000
No. 4	OpenFOAM [17] modeled in 2D, min. mesh size = 1.5 mm
No. 5	OpenFOAM [17] mesh size = 3 - 10 mm
No. 6	FEFLO [18] mesh size = 5 - 20 mm
No. 7	OpenFOAM [17] modeled in 2D, mesh size = 5 mm

Table 2, Figs. 6 and 7 compare the calculated forces with the experimental results. The results are summarized as follows:

a) Some lines in Figs. 6 and 7 show high frequency time histories. If we model the numerical field precisely, the obtained raw data show the high frequency time histories. So the designers should use an appropriate moving average method to use the results in the design of bridges. Furthermore, we have to determine how precise we should model a real bridge.

b) All participants calculated horizontal forces generally corresponding to the test results. However, all of them overestimated the impact force when the wave first arrived at the model. Although this increased the safety of the estimation, we need to investigate the cause.

c) The estimation of the vertical force was less accurate than that of the horizontal force. Even if we modeled the bridge as a 2D rectangle, we could estimate the approximate horizontal force to act on it. On the other hand, the vertical force was difficult to estimate unless we modeled it precisely in 3D. The bridge shape as well as the gap between the model and the wall should be modeled with high precision, because the wave that separates at the edge of the bridge has a big impact on the vertical force.

Table 2 – Maximum and minimum forces in Case 1

	Max. drag	Max. lift	Min. lift
Experiment	19.9	47.7	–47.5
No. 1	19.1	41.2	–51.3
No. 2	29.3	42.1	–50.0
No. 3	24.3	56.6	–44.2
No. 4	19.2	88.6	–118.2
No. 5	20.3	67.1	–52.7
No. 6	28.0	88.8	–37.7
No. 7	25.4	83.8	–76.1

(unit: N)

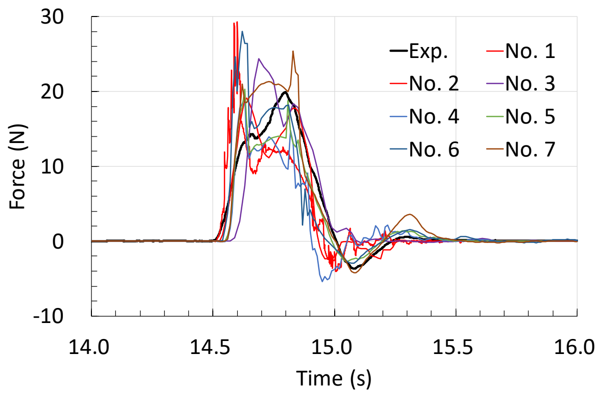


Fig. 6 – Drag-time histories for Case 1

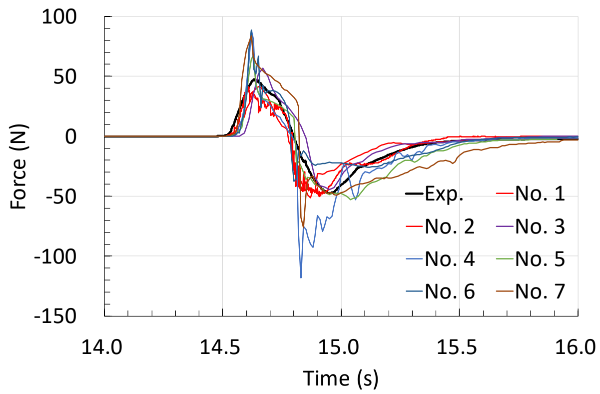


Fig. 7 – Lift-time histories for Case 1

3. 2 Case 2: skewed bridge

Eight participants used CFD software, as shown in Table 3. Table 4 and Figs. 8 to 10 compare the calculated forces with the experimental results. The results are summarized as follows:

a) All participants calculated horizontal transverse forces perpendicular to the bridge axis at 85%-150% of the experimental result, which was accurate enough to be used as an estimate tsunami force for the bridge anti-tsunami design.

b) The estimation of the vertical force was less accurate than that of the horizontal transverse force. The percent difference between the estimate and the experimental results was 50%-200%. The separating wave at the edge of the bridge model, which was very difficult to simulate accurately, affected much on the vertical force.

Table 3 – Software used in Case 2

	Software
No. 1	FEM original code [19] mesh size = 2 mm
No. 2	SPH DualSPHysics [16] number of particles = 700,000
No. 3	OpenFOAM [17] / interDyMFoam, mesh size = 2 - 5 mm
No. 4	SPH DYBECS [20] number of particles = 600,000
No. 5	OpenFOAM [17] / interFoam, mesh size = 0.5 - 10 mm
No. 6	FEM original code [21] min. mesh size = 2 mm
No. 7	SPH original code [22] number of particles = 2,500,000
No. 8	FEFLO [18] mesh sizes = 2.5 - 20 mm

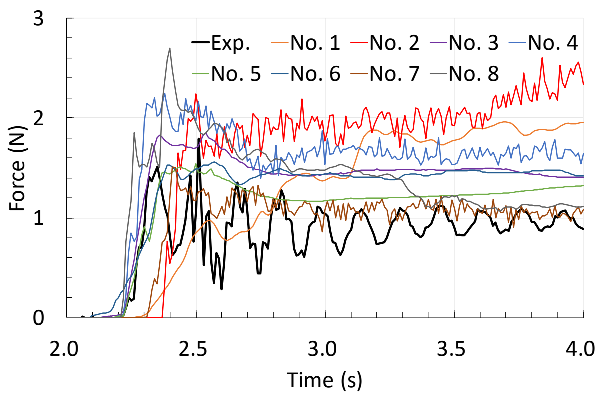


Fig. 8 – Transverse force-time histories

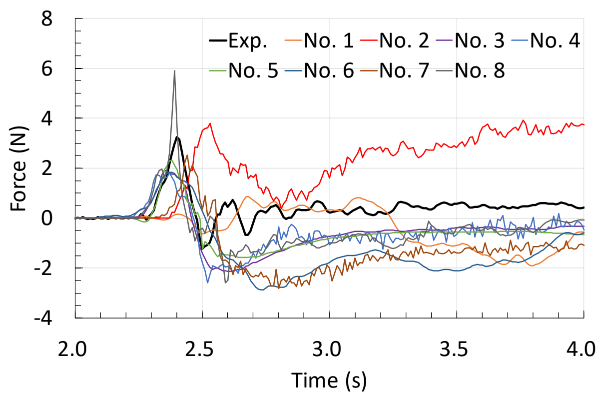


Fig. 9 – Lift-time histories

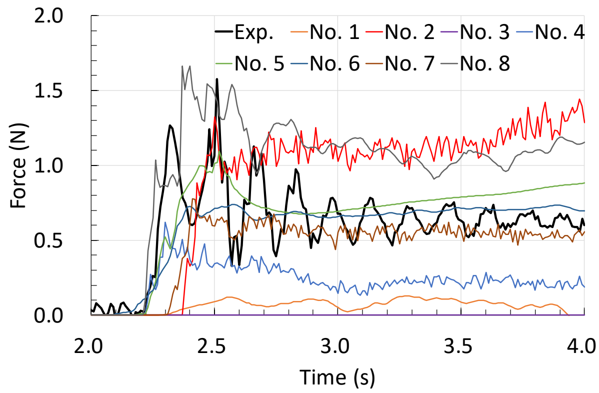


Fig. 10 – Longitudinal force-time histories

c) The estimation of the horizontal longitudinal force was not very accurate. The longitudinal force was ideally zero if the girder continued indefinitely. However, there was a gap between the model and the wall, which caused the pressure in the longitudinal direction. Further, the bridge model vibrated owing to the impact of the tsunami because of the weak cantilever support, which changed the wave direction moment by moment. This change in wave direction also affected the longitudinal force, which was not considered in the numerical calculations. All the participants treated the model as a rigid body at rest.

Table 4 – Maximum and minimum forces in Case 2

(unit: N)	Max. TR	Max. lift	Min. lift	Max. LN
Experiment	1.8	3.2	–1.2	1.6
No. 1	2.0	0.9	–1.9	0.1
No. 2	2.6	3.9	0.0	1.4
No. 3	1.8	1.9	–2.1	0.0
No. 4	2.2	1.8	–2.6	0.6
No. 5	1.5	2.3	–1.6	1.1
No. 6	1.6	1.8	–2.9	0.7
No. 7	1.5	2.5	–2.8	0.8
No. 8	2.7	5.9	–2.6	1.7

TR: transverse, LN: Longitudinal (unit: N)

d) Case 2 used models with and without skew having the same projected area. However, the real skewed bridge has the same width as the bridge without skew, which results in a wider projected area than that of the non-skewed one. This increase in projected area has the potential to cause an increase in the vertical force.

e) As the participants could refer to the experimental results for the model without skew in advance, they submitted good estimation for the tsunami forces to the model without skew. However, the accuracy was lower compared to Case 1, because the bridge model without skew in Case 2 also showed vibration like the model with skew shown in Figs. 8 to 10. Effects of the dynamic interaction between the structure and the water were difficult to analyze. However, this interaction should be considered for the bridges supported by soft rubber bearings, as they are liable to vibrate due to horizontal forces.

4. Concluding remarks

During the symposium, participants discussed the differences between the numerical methods as well as the techniques that could be used to improve accuracy. Digital proceedings are available on the website of the subcommittee on Anti-Tsunami De-sign Methods for Bridges [23]. We hope these proceedings will be used as a reference and guideline in the design of countermeasures to incorporate into bridges to allow them to withstand tsunamis.

5. Appendix

Subcommittee members are as follows: Kazuyuki Izuno (Chair, Ritsumeikan University), Kenji Kosa (Vice-Chair, Kyushu Institute of Technology), Shuhei Takeda (Secretary General, Fukui University of Technology), Hisashi Nakao (Secretary, Public Works Research Institute), Yuma Kawasaki (Secretary, Ritsumeikan University), Mitsuyoshi Akiyama (Waseda University), Kenji Arakawa (JIP Techno Science Corporation), Mitsuteru Asai (Kyushu University), Kazuya Gushi (Nippon Engineering Consultants Co., Ltd.), Akira Igarashi (Kyoto University), Yoshihisa Maruyama (Chiba University), Tomoaki Nakamura (Nagoya University), Katsuyoshi Nozaka (Ritsumeikan University), Munemasa Ogawa (CTI Engineering Co., Ltd.), Tatsuo Sasaki (Nippon Engineering Consultants Co., Ltd.), Takashi Sato (Chodai Co., Ltd.), Yoshinori Shigihara (National Defense Academy of Japan), Gaku Shoji (University of Tsukuba), Seizo Tanaka (University of Tsukuba), Kenji Tasaki (Nippon Engineering Consultants Co., Ltd.), Kunihiro Yamauchi (IHI Corporation) and Nozomu Yoneyama (Kyoto University).

6. References

[1] Shoji G, Hiraki Y, Fujima K, Shigihara Y (2011): Eval-uation of tsunami fluid force acting on a bridge deck sub-jected to breaker bores. *12th East Asia-Pacific Conference on Structural Engineering and Construction, Procedia Engineering*, 14, 1079-1088.

[2] Zhang G, Hoshikuma J, Usui T (2010): A study on countermeasure for reducing effect of tsunami on highway bridges, *26th US-Japan Bridge Engineering Workshop*, Tsukuba, Japan.

[3] Kawasaki Y, Izuno K (2013): Mitigation of the impact of tsunamis on bridges. *Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics*, Vienna, Austria.

[4] Yoneyama N, Naota A (2013): Applicability of VOF-method-based numerical analysis to the estimation of the tsunami force acting on a bridge. *35th IAHR World Congress*, Chengdu, China.

[5] Akiyama M, Frangopol DM, Arai M, Koshimura S (2013): Reliability of bridges under tsunami hazards. *Earthquake Spectra*, **29** (S1), S295-S314.

[6] Yeh H, Barbosa AR, Ko H, Cawley JG (2014): Tsunami loadings on structures: review and analysis. *Coastal Engineering Proceedings*, **34**, 1-13.

[7] Fu L, Kosa K, Sasaki T, Sato T (2014): Tsunami force on bridge comparison of two wave types by experimental test. *Journal of Structural Engineering*, JSCE, **60A**, 282-292.

[8] Bricker J, Nakayama A (2014): Contribution of trapped air, deck superelevation, and nearby structures to bridge deck failure during a tsunami. *Journal of Hydraulic Engineering*, 10.1061/(ASCE) HY.1943-7900.0000855.

[9] Azadbakht M, Yim S (2014): Simulation and estimation of tsunami loads on bridge superstructures. *Journal of Waterway, Port, Coastal, Ocean Engineering*, 10.1061/(ASCE)WW.1943-5460. 0000262, 04014031.

[10] Motley M, Wong H, Qin X, Winter A, Eberhard M (2015): Tsunami-induced forces on skewed bridges. *Journal of Waterway, Port, Coastal, Ocean Engineering*, 10.1061/(ASCE)WW.1943- 5460.0000328, 04015025.

[11] Miyagawa Y, Asai M (2015): Multi-scale bridge wash out simulation during tsunami by a stabilized ISPH method. *3rd International Conference on Civil and Environmental Engineering for Sustainability*.

[12] Wei Z, Dalrymple RA (2016): Numerical study on miti-gating tsunami force on bridges by an SPH model. *Journal of Ocean Engineering Marine Energy*, **2** (3), 365-380, 10.1007/s40722- 016-0054-6.

[13] Tanaka M, Kosa K, Sasaki T, Sato T (2015): Evaluation of horizontal force on bridge girder due to soliton. *Journal of Structural Engineering*, JSCE, **61A**, 246-255 (in Japanese).

[14] Tanaka M, Kosa K, Sasaki T, Sato T (2015): Evaluation for the vertical force acting on the bridge girder due to the tsunami with solitary wave. *Journal of JSCE*, B2, **71** (2), I_973-I_978 (in Japanese).

[15] Coastal Development Institute of Technology (2010): *Research and Development of Numerical Wave Tank "CADMAS-SURF /3D"* (in Japanese).

[16] Crespo AAJC, Domínguez JM, Rogers BD, Gomez-Gesteira M, Longshaw S, Canelas R, Vacondio R, Barreiro A, Feal OG (2015): DualSPHys-ics: open-source parallel CFD solver on Smoothed Particle Hydrodynamics (SPH) . *Computer Physics Communications*, **187**, 204-216.

[17] The OpenFOAM Foundation: OpenFOAM - Official home of The Open Source Computational Fluid Dynamics (CFD) Toolbox. https://openfoam.org/

[18] Löhner R (2001): *Applied CFD Techniques*, John Wiley & Sons.

[19] Tanaka S, Sun F, Hori M, Ichimura T, Wijerathne MLL (2013): Development of failure analysis method of structure due to tsunami impact. *10th International Conference on Urban Earthquake Engineering*, Tokyo, Japan.

[20] Watanabe T, Masuya H, Mitsuhashi Y (2013): Fundamental study on the numerical simulation procedure of wall boundary with large deformation under impact by smoothed particle hydrodynamics method, *Transactions of JSCE*, 20130021 (in Japanese).

[21] Takase S, Moriguchi S, Terada K, Kato J, Kyoya T, Kashiyama K, Kotani T (2016): 2D-3D hybrid stabilized finite element method for tsunami runup simulations, *Computational Mechanics*, **58**, 411-422.

[22] Asai M, Aly AM, Sonoda Y, Sakai Y (2012): A stabilized incompressible SPH method by relaxing the density invariance condition, *International Journal of Applied Mathematics*, **2012**, ID 139583.

[23] Subcommittee on Anti-Tsunami Design Methods for Bridges (2016): http://committees.jsce.or.jp/eec209/node/12, The Earthquake Engineering Committee, JSCE.

