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# **Coastal Road Slope Disasters due to Scour and Erosion surrounding a Retaining Wall**

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## **ABSTRACT**

This study investigated two coastal road slope disasters that occurred due to scour and erosion on 2 December 2014 and on 23 November 2021, in Hokkaido, Japan. The two disasters represented coastal collapses behind a retaining wall under high wave conditions during winter storms. The results of the field surveys showed that the extent of collapses was significantly larger in the 2014 disaster than in the 2021 disaster, where the former event was accompanied by wave-induced overtopping. A series of hydraulic wave flume experiments were conducted so as to gain insights into the disaster mechanisms. The experimental results combined with the field surveys demonstrated that both disasters share the same basic mechanisms, owing to coupled surface erosion, scour and internal erosion beneath and behind the retaining wall, which led to collapse. Notably, the existence of overtopping flow enlarged the extent of collapses in the 2014 disaster compared with the 2021 disaster.

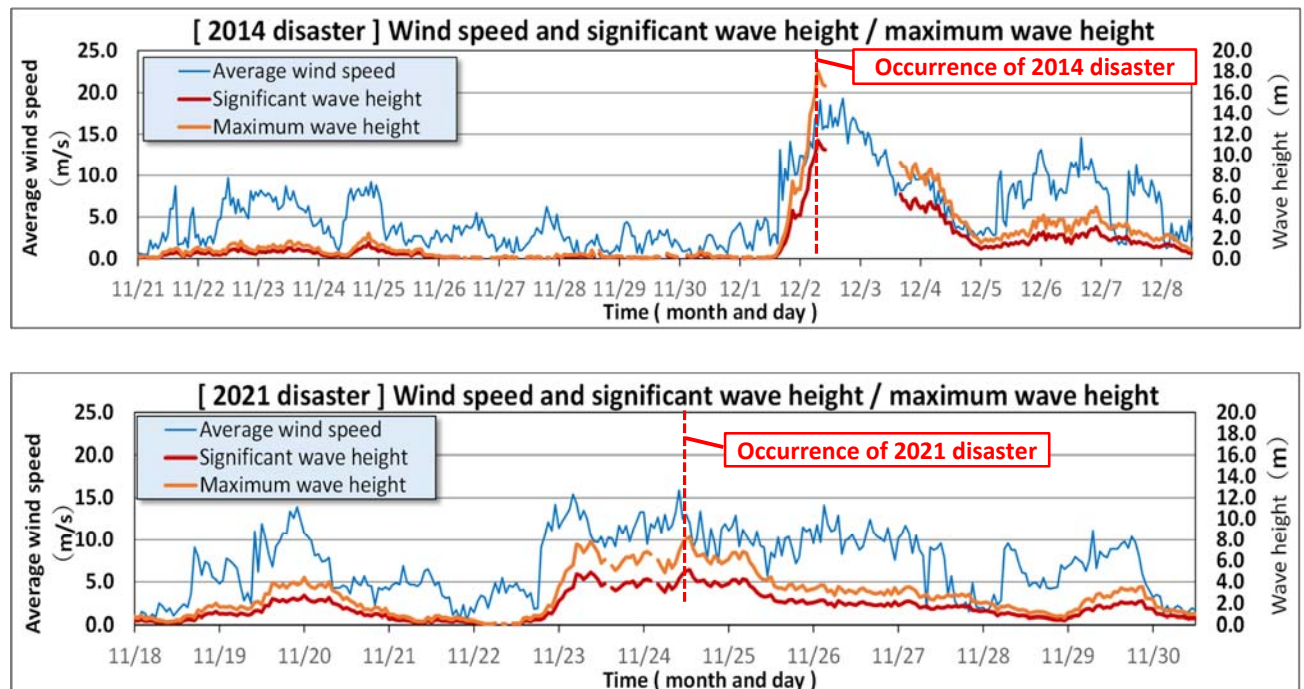
## **INTRODUCTION**

Ongoing and future global climate change is expected to increase the severity of wave conditions along coasts worldwide (Morim et al., 2019). Coastal roads are subjected to the risks of high waves, overtopping, and flows, which threatens the safe passage of vehicles and humans. In Japan, the main traffic routes are often located in the immediate vicinity of the coastline. Seasonal wave effects such as typhoons and winter storms have occasionally caused damages to coastal roads owing to scour and erosion. A better understanding of the disaster risks and associated mechanisms

is therefore essential for the conservation and maintenance of coastal roads. This study aims to investigate two coastal road disasters that took place on 2 December 2014 and on 23 November 2021 in Hokkaido, Japan, based on the field surveys and hydraulic model experiments. Below, the results from the field surveys conducted for the coastal road slope collapses behind retaining walls are described first. This is followed by the results of a series of hydraulic wave flume experiments performed. The combined results of the field and experimental investigations are then discussed and summarized in the Conclusion.

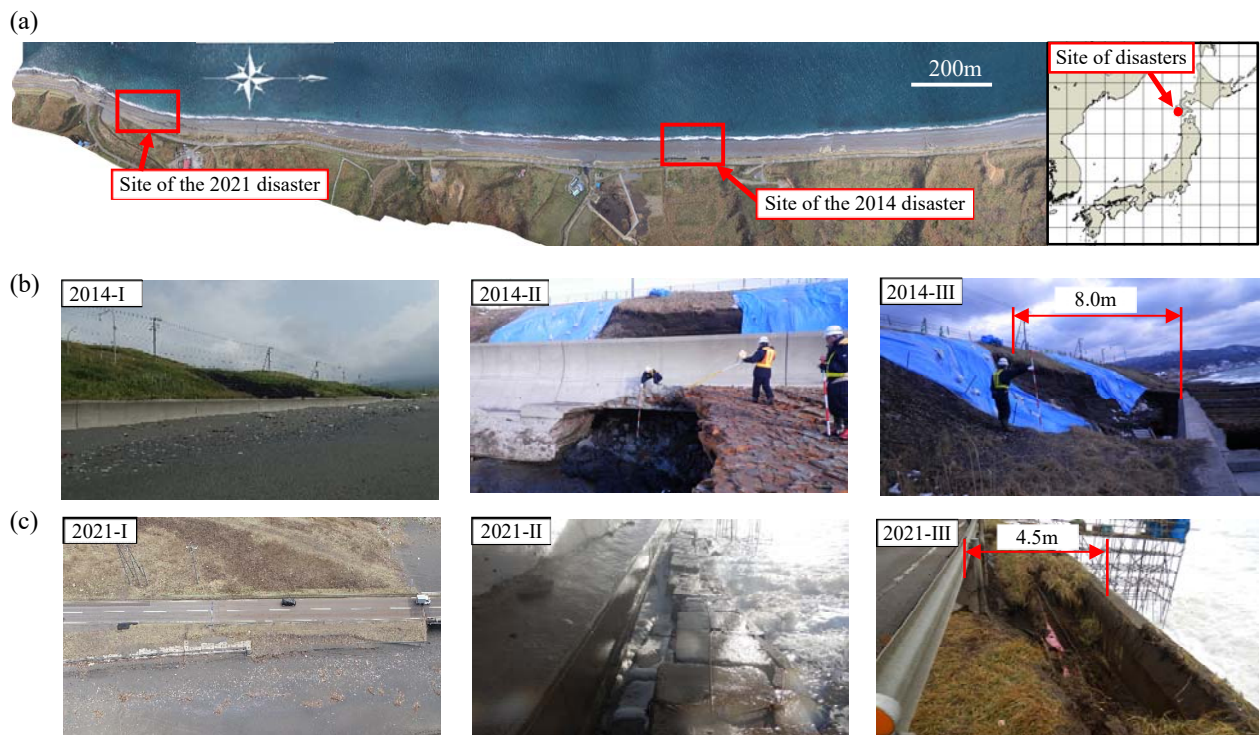
## FIELD SURVEYS OF THE 2014 AND 2021 COASTAL DISASTERS

The 2014 and 2021 disasters took place during winter storm seasons which caused high wave conditions along the Ohanzaiham coast in Hokkaido, Japan (Figures 1 and 2). The measured time histories of the maximum and significant wave heights and the average wave speeds at and around the times of the 2014 and 2021 disasters are shown in Figure 1. During the 2014 event, the maximum wave height reached 18.07 m, with a maximum significant wave height of 11.41 m under an average wind speed of 19.1 m/s on 2 December 2014. During the 2021 event, the maximum wave height reached 8.25 m, with a maximum significant wave height of 5.05 m shortly after recording an average wind speed of 15.9 m/s on 24 November 2021. Here, the significant wave height is defined as the average height of the highest one-third of all waves, and the maximum wave height denotes the largest measured wave at a given location.



**Figure 1. Time histories of significant and maximum wave heights and average wind speeds at/around the times of 2014 and 2021 disasters.**

The field surveys were conducted several days after the 2014 and 2021 events, as shown in Figure 2. The photographs 2014-I and 2021-I show normal times in 2019, where the foreshores were covered with sand and no significant erosion took place. In contrast, the photographs 2014-II and 2021-II show that the foreshore sands were lost, owing to surface erosion that occurred under the action of high waves; subsequently, the base and foundation of the retaining walls were exposed. At the site of the 2014 event, there existed a weak erodible bedrock as alternate layers of mudstone and sandstone beneath sands (2014-II). The photographs 2014-III and 2021-III indicate that large collapses took place in the coastal road slopes behind retaining walls. The extent of collapses during the 2014 event was equal to 8.0 m, which was significantly larger than that of 4.5 m during the 2021 event. The trace of peeling of vegetation was also identified on the road slope surface behind the retaining wall following the 2014 event, whereas it was not confirmed following the 2021 event. This suggests that the severe wave-induced overtopping flows acted behind the retaining wall at the time of the 2014 event. The associated mechanisms will be discussed later in this paper.

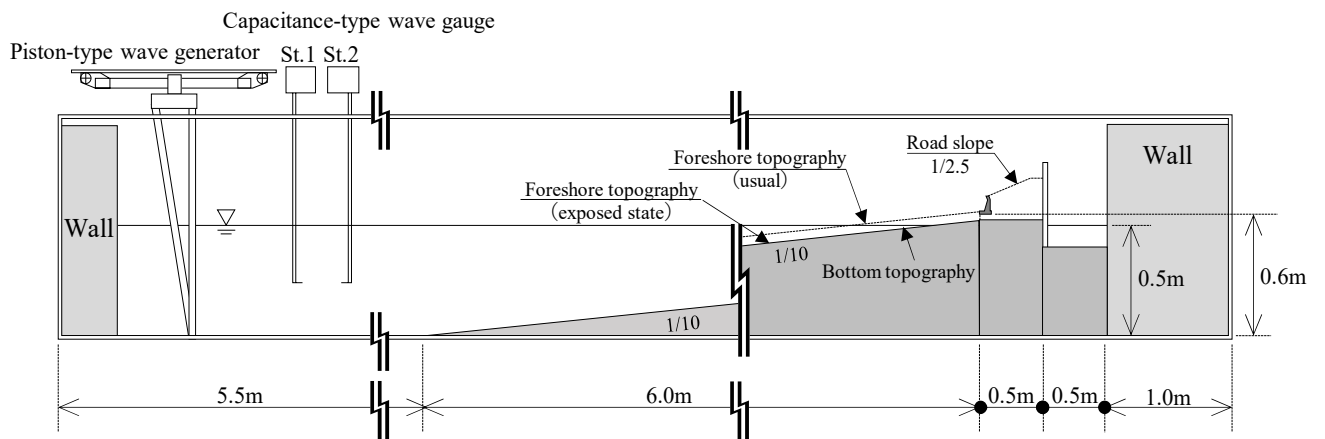


**Figure 2. Field surveys of the 2014 and 2021 disasters. (a) Site of disasters, (b) Situations at a normal time (2014-I) and following the 2014 disaster (2014-II, 2014-III), (c) Situations at a normal time (2021-I) and following the 2021 disaster (2021-II, 2021-III)**

## WAVE FLUME EXPERIMENTS ON THE COASTAL ROAD SLOPES BEHIND A RETAINING WALL

### Material and Method

A series of hydraulic model experiments were conducted on a two-dimensional cross-section using a wave flume at the National Institute of Technology, Hakodate College, in Hokkaido, Japan. The wave channel was 13.5 m long, 0.9 m high, and 0.5 m wide and had a piston-type wave-maker at the left end of the channel (Figure 3). The scale of the experiments was 1/50th with reference to the foreshores and retaining walls at the site of the 2014 and 2021 disasters described above. At the site of the disasters, the five-year probability wave had the significant wave height  $H_{1/3} = 6.7$  m and the significant wave period  $T_{1/3} = 12.9$  s, and the one-year probability wave had the significant wave height  $H_{1/3} = 4.6$  m and the significant wave period  $T_{1/3} = 10.7$  s. On the basis of the Froude similarity law, these field wave conditions were converted to irregular waves with the offshore significant wave heights of 13.4 cm ( $6.7 \text{ m}/50$ ) and 9.2 cm ( $4.6 \text{ m}/50$ ) and the offshore significant wave periods of 1.82 s ( $12.9/\sqrt{50}$ ) and 1.51 s ( $10.7/\sqrt{50}$ ) respectively, using the Bretschneider-Mitsuyasu (BM) spectrum that is widely known to represent fully-grown wind waves (Bretschneider, 1970; Tsubokawa et al., 2023). The coastal bottom slope gradient was set equal to 1/10 and the coastal road slope gradient behind the top of the retaining wall was set equal to 1/2.5 in light of the field. The sand used was silica sand with a median grain diameter  $d_{50} = 0.42$  mm. This was determined with reference to the measured permeability coefficient  $k_w = 0.038$  cm/s that was 1/√50 -scale of the measured permeability coefficient  $k_w = 0.267$  cm/s of the foreshore sand ( $d_{50} = 1.24$  mm) in the field.



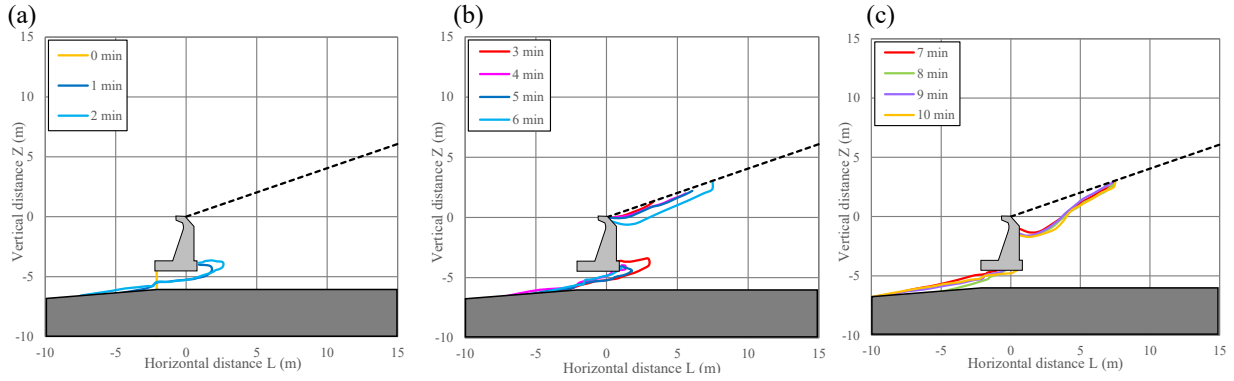
**Figure 3. Cross-section of a two-dimensional wave flume at National Institute of Technology, Hakodate College, Hokkaido, Japan and the experimental setup for the 2014 and 2021 coastal road slope disasters**

It may be important here to note that the similitudes for wave-soil interactions involving sediment transport and pore water pressures in the soil have not yet been established. Therefore, the purpose of the present experiments was to gain insights into the mechanisms of the 2014 and 2021 disasters. In two series of experiments, the first series targeted the 2014 disaster under the five-year probability wave. The initial condition was such that the base of the retaining wall was already exposed due to surface erosion. The second series targeted the 2021 disaster under the one-year probability wave. The foreshore sand existed at the start of the experiment. The wave-induced flow velocity above the foreshore sand was of the order of 20-30 cm/s, which fell in the bedload regime (Yang et al., 2019). For both series of experiments, sand beds were formed by pouring dry sands and the water levels were set at a high-water level (H.W.L.). Approximately 400 wave cycles corresponding to a duration of 70 minutes on a prototype scale were applied, and the progresses of surface erosion, scour, internal erosion, and collapse were monitored by a digital video camera and analyzed via a digitizer for both series of experiments.

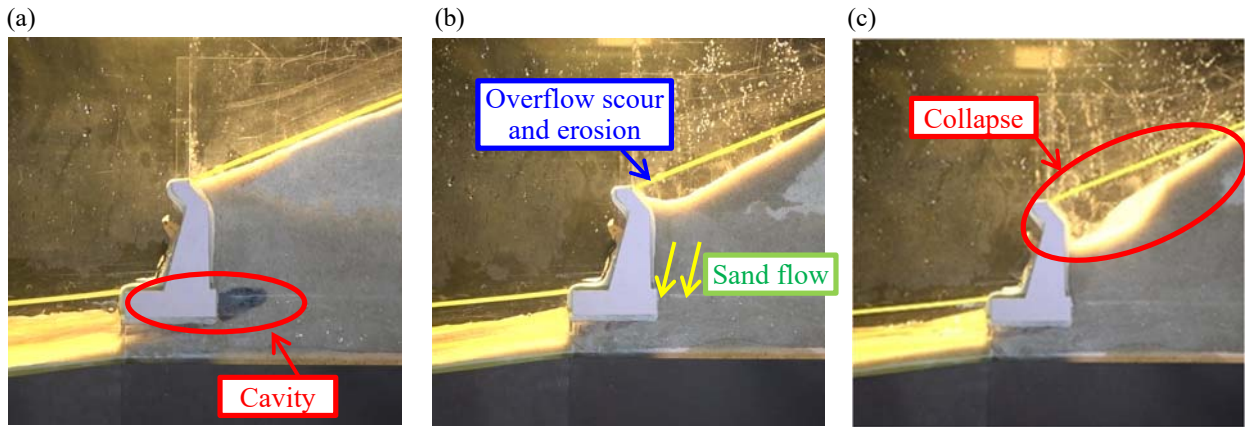
### **Experimental Results**

The results of the first series of the wave flume experiment for the 2014 disaster are shown in Figures. 4 and 5. At the start of the experiment, the base of the retaining wall was already exposed. The five-year probability wave gave rise to the occurrence of internal erosion beneath the base of the retaining wall. This was accompanied by the formation of a cavity, and the cavity developed towards the back of the retaining wall (Figure 4a and Figure 5a). Meanwhile, the overtopping induced by the five-year probability wave caused scour and erosion behind the top of the wall. A close examination of Figure 5b tells us about the repeated development and decline of the internal cavities formed around the rear of the retaining wall. Eventually, the continued action of the five-year probability wave brought about a large collapse in association with the destabilization of the cavities surrounding the retaining wall. The extent of the collapse was equal to 7.5 m on a prototype scale, which was consistent with that of 8 m as a result of the field measurement for the 2014 disaster described above. The concurrent processes of the cavity occurrence, overflow scour and erosion, sand flow, and collapse can be more directly seen from the photographs shown in Figure 5.

The results of the second series of the wave flume experiment for the 2021 disaster are shown in Figure 6. Here, Figure 6a shows the contour of temporal deformations as a consequence of the one-year probability wave. The results indicate that the foreshore sands were lost due to surface erosion and scour in front of the base of the retaining wall. Under the continued action of the one-year probability wave, the internal erosion progressed beneath and behind the retaining wall, and collapse occurred. The extent of the collapse, however, was significantly smaller than the extent of collapse manifested under the five-year probability wave that accompanied overtopping (Figures 4c and 5c). Figure 6b shows the situation of collapse under the one-year probability wave, that is to say, in the absence of overtopping. It is noteworthy that the time required to give rise to collapse was substantially longer in the case of the one-year probability wave compared with the



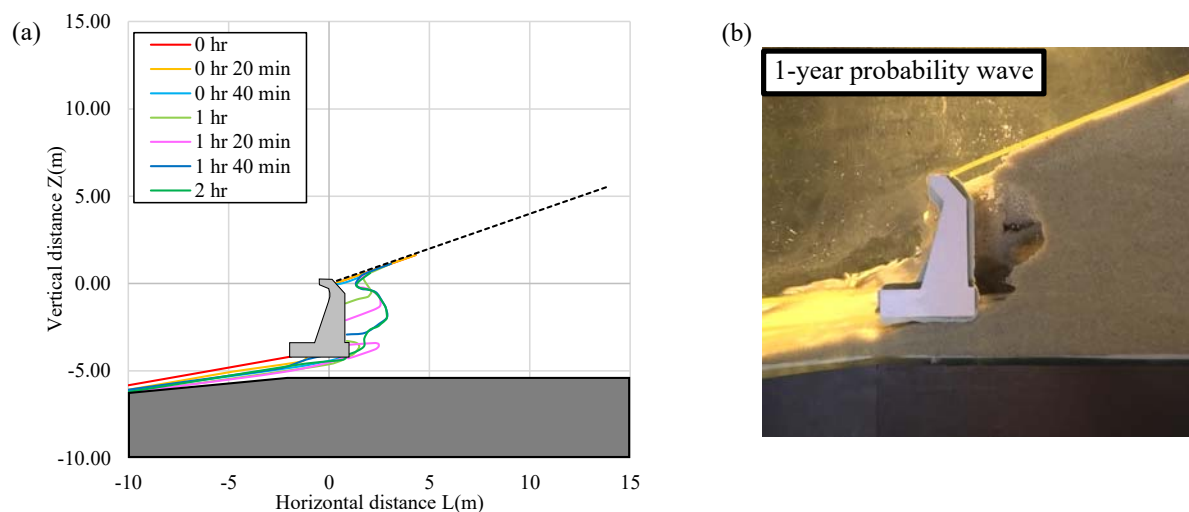
**Figure 4. Results of the wave flume experiment for the 2014 disaster. Progress of internal erosion and collapse beneath/behind the retaining wall at (a) 0 to 2 min and (b) 3 to 6 min and (c) 7 to 10 min after the start of the experiment. Contours on a prototype scale.**



**Figure 5. Results of the wave flume experiment for the 2014 disaster. Progress of internal erosion and collapse beneath/behind the retaining wall at (a) 2 min and (b) 6 min and (c) 10 min after the start of the experiment. Photographs.**

five-year probability wave (Figures 4c and 6a).

The combined results from the field surveys and a series of wave flume experiments indicate that the wave-induced runup and return flow acted on the foreshore sands, which caused surface erosion and scour in front of the base of the retaining wall. The continued severe wave action then gave rise to the occurrence of progressive internal erosion, accompanied by the formation of cavities beneath and behind the retaining wall. The occurrence of wave overtopping/overflow resulted in the scour and erosion of the road slope surface. It is important to note that the overflow decreases suction in the ground, which destabilizes cavities formed by the internal erosion under waves (Kudai et al., 2021), and the overflow promotes flow-out of granular materials beneath a foundation of coastal structures (Sassa et al., 2016). Hence, the coupled severe wave action and overflow brought about a large collapse and sand flow-out surrounding the retaining wall. In the case of the one-year probability wave, however, the simultaneous surface erosion and internal



**Figure 6. Results of the wave flume experiment for the 2021 disaster. Progress of internal erosion and collapse beneath/behind the retaining wall after the start of the experiment. (a) Contours on a prototype scale and (b) Photographs.**

erosion beneath and behind the retaining wall led to collapse in the absence of overtopping. Hence, these results demonstrate an important role of the wave-induced internal erosion beneath and behind the retaining wall in causing the coastal road slope disasters.

## CONCLUSION

The processes and mechanisms for the 2014 and 2021 coastal road slope disasters were investigated based on the field surveys and a series of wave flume experiments. The results demonstrate that both of the 2014 and 2021 disasters share the same basic mechanisms, namely, the coupled surface erosion, scour, and internal erosion beneath and behind the retaining wall brought about collapses subject to waves, flows, and overtopping. The extent of collapses in the 2014 disaster was enlarged due to the existence of the overtopping flow in the light of the 2021 disaster.

## REFERENCES

- Bretschneider, C.L. (1968). Significant waves and wave spectrum, In Ocean Industry; Gulf Publishing Company: Houston, TX, USA.
- Kudai, K., Sassa, S., Yang, S., and Takada, K. (2021). "Influence of soil and hydraulic conditions on the processes of internal erosion, cavity formation and collapse behind coastal structures." *Coastal Engineering*, 170, 104013.
- Mitsuyasu, H. (1970). "On the Growth of Wind-Generated Waves (2)—Spectral Shape of Wind Waves at Finite Fetch." *Proc. of the 17th Japanese Conference*, Kyoto, Japan.

- Morim, J., Hemer, M., Wang, X.L., Cartwright, N., Trenham, C., Semedo, A., Young, I., Bricheno, L., Camus, P., Casas-Prat, M., Erikson, L., Mentaschi, L., Mori, N., Shimura, T., Timmermans, B., Aarnes, O., Breivik, O., Behrens, A., Dobrynin, M., Menendez, M., Staneva, J., Wehner, M., Wolf, J., Kamranzad, B., Webb, A., Stopa, J., and Andutta, F. (2019). "Robustness and uncertainties in global multivariate wind-wave climate projections." *Nature Climate Change*, 9, 711–718.
- Sassa, S., Takahashi, H., Morikawa, Y., and Takano, D. (2016). "Effect of overflow and seepage coupling on tsunami-induced instability of caisson breakwaters." *Coastal Engineering*, 117, 157–165.
- Tsubokawa, R., Iida, Y., Ushiwatari, Y., Matsuda, T., Ochi, M., Miyatake, M. and Sassa, S. (2023). "Coastal Road Slope Collapses behind a Retaining Wall due to Scour and Erosion." *International Journal of Geoengineering Case Histories* 7(4), 39-49.
- Yang, Y., Gao, S., Wang, Y.P., Jia, J., Xiong, J., and Zhou, L. (2019). "Revisiting the problem of sediment motion threshold." *Continental Shelf Research*, 187, 103960.