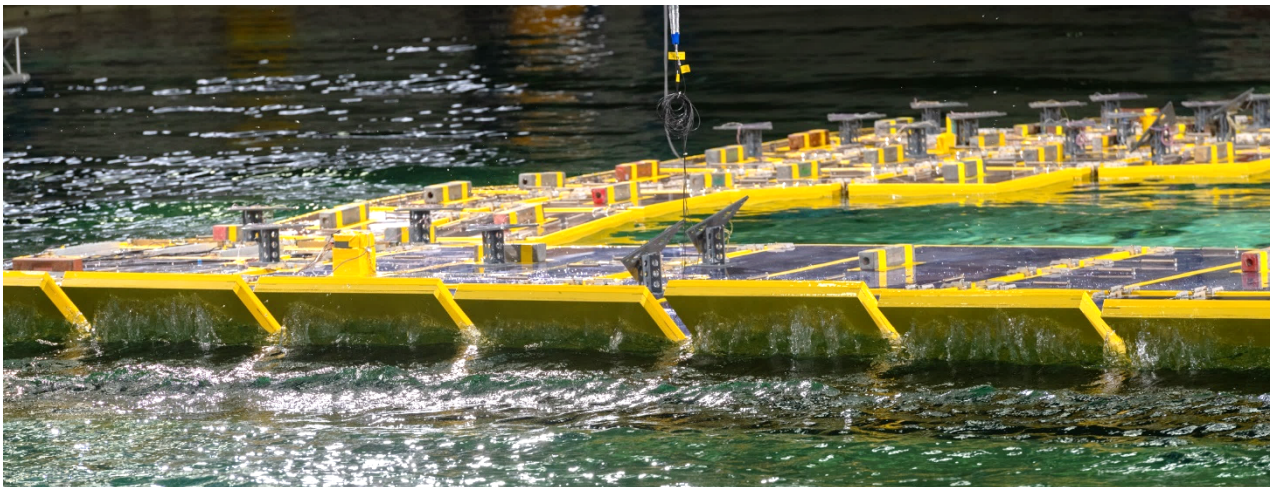

Figure 6-9: WECs showing large pitch amplitudes in 100yrs storm

For waves approaching under an angle, the WECs show large pitch amplitudes, too, see Figure 6-10. To further increase the efficiency in relevant energetic sea states, the WEC's width should be optimized in future studies. In parallel, however, the best ratio of width and unit related fix costs per WEC needs to be assessed in order to reduce the levelized costs of energy.

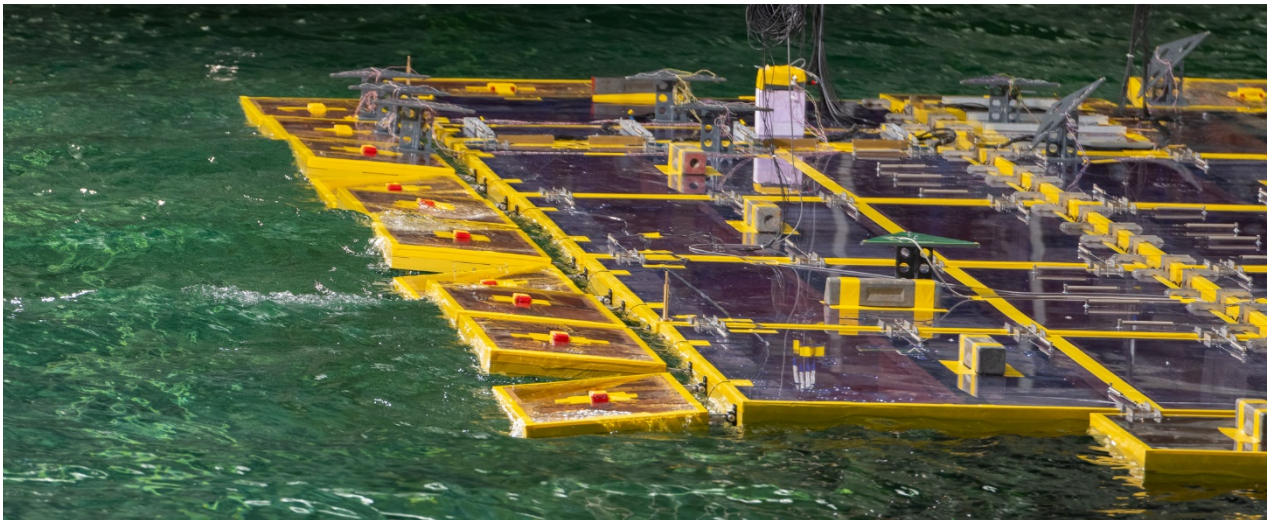

Figure 6-10: WECs showing large amplitudes also for waves approaching under an angle

6.4.2 Fender load response

Fender forces were measured at 10 locations in the assembly. The MPM values for compression are summarized in Figure 6-11. During the tests there was no tension measured in the fenders, in other words the pretension of the rope wires is sufficient to maintain compression in the fenders in waves and current. For compression, it can be seen that fender L1-1 and L12-4 are the ones which have the highest loading. Hence, L1-1 is the fender between module L1 and L7 on the outer side, L12-4 is the fender between module L12 and M2 on the outer side. The frequency content of this compression is shown in Figure 6-12. For the fender L12-4, there is a slender but strong low frequent response. This is an eigen-mode of the assembly where the cluster of small modules is hinging around the point where the small modules are connected to the large modules. The sharp peak suggests a lightly damped eigen-mode. Both fenders show a wave frequent response around 0.5 rad/s to 1.0 rad/s. Interesting is the high frequent response between 1.0 rad/s and 1.5 rad/s. There

is no wave energy around this frequency. It is plausible that this response is caused by second order sum-frequent drift forces.

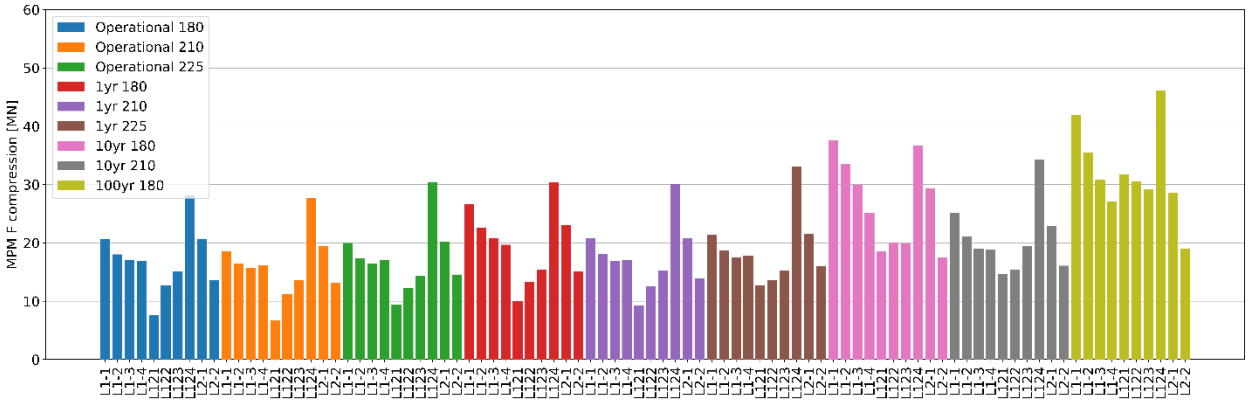

Figure 6-11: MPM Compression force fenders including pre-compression

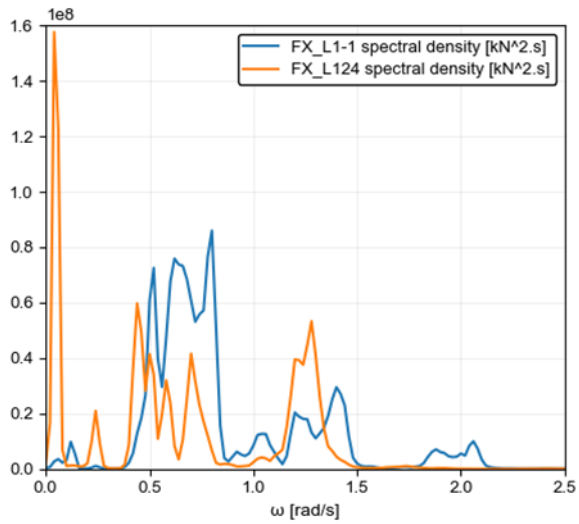

Figure 6-12: Spectral density compression in fender L1-1 and L12-4, 100 year condition

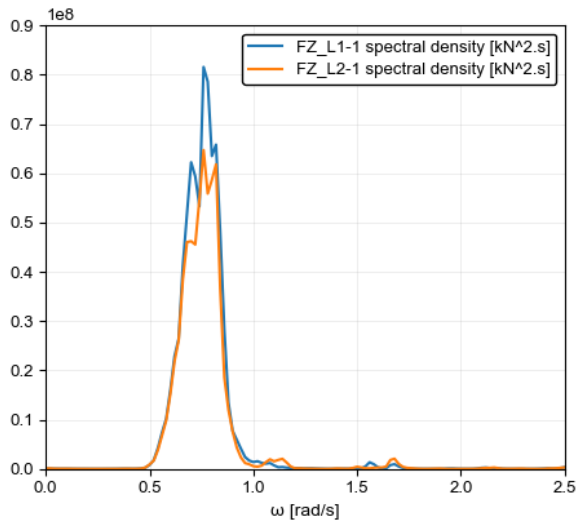

Figure 6-13 Spectral density vertical shear fender L1-1 and L12-4, 1 yr 225degrees

The standard deviation of the vertical shear forces in the fenders is shown in Figure 6-14. Especially for fender L1-1, it can be seen that the shear force increases with the wave direction. For 180 degrees, the wave propagation is in line with the fender, while for 225 degrees the propagation is oblique to the fender. Due to the square geometry of the modules, this direction leads to the highest vertical shear. It should be noted that for this reason the highest sea states were not tested oblique.

In Figure 6-13 it can be seen that the shear force in the fenders is purely wave frequent. No low or high frequent resonance occurs in this direction. Most likely that is because the radiation damping in pitch is high, preventing resonance.

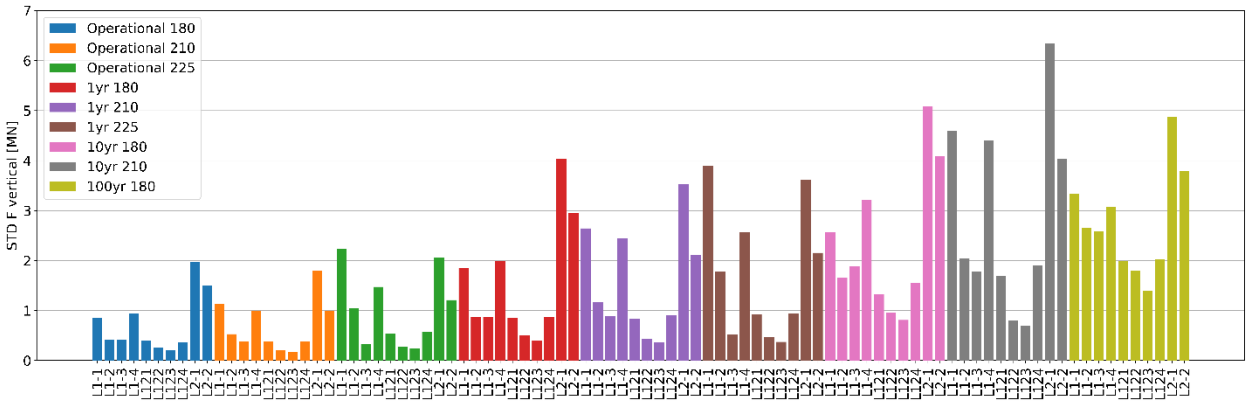

Figure 6-14: Standard deviation vertical shear force in fenders

6.4.3 Mooring line load response

The maximum measured line load is shown in Figure 6-15 and Figure 6-16. Note that only the lines wave ward from 180degrees are shown, all other lines have lower loading. It should be noted that the bundling factor of the mooring lines is 2, in other words, one line in the test represents 2 lines in reality. The line tension presented here can therefore be divided by two. The MBL of the lines is 15.442 kN. It can be seen that the measured line tensions are all below the MBL, resulting in a safety factor slightly higher than 2 because of the bundling factor. Also, it can be seen that in general there is not so much difference between the tests with and without current, except for the 100 year case. Here the difference between with and without current is almost a factor two. The main cause of this sudden increase is, that in the test with current, there was lift-off at the anchor. It is therefore expected that if the mooring radius and line length would be increased, the loads would reduce significantly in this case.

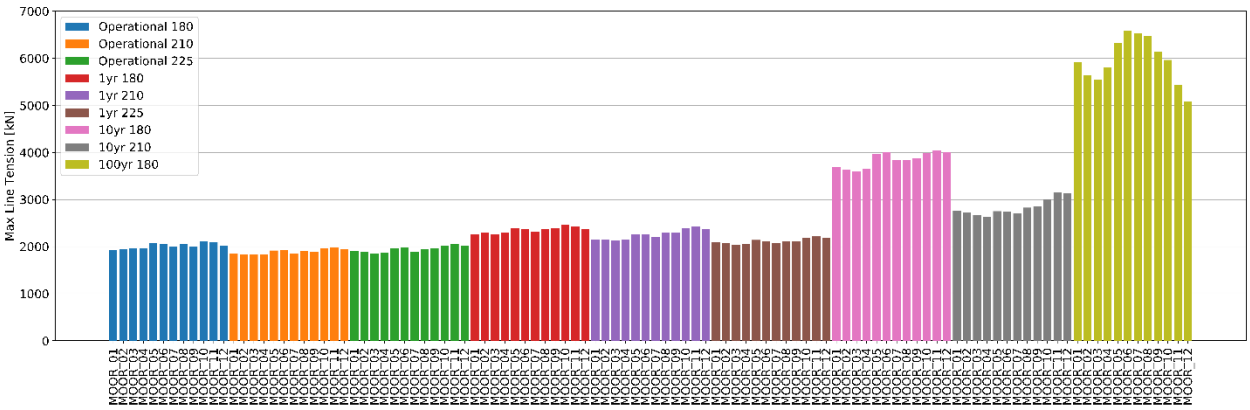

Figure 6-15 Maximum line load, cases without current

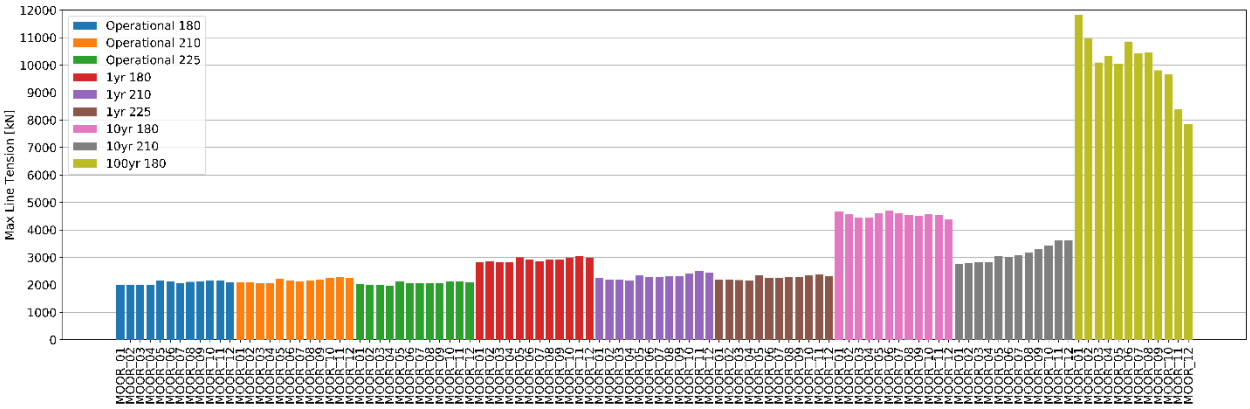

Figure 6-16: Maximum line load, cases with current

6.4.4 Greenwater on Deck

In storm sea states with wave heights above approximately 5m and wave periods close to pitch resonance (wave periods of about 10 s), significant green water on deck of the wave ward modules has been observed, see Figure 6-17. It is expected (but has not been tested) that longer sea states with wave periods of about 30 s, show a less critical so called 'wave riding', where the modules better follow the waves, see Figure 6-18.

Figure 6-17: Green water on deck of the waveward Space@Sea modules in a 100yrs storm

Figure 6-18: Wave riding with sufficient freeboard

Whereas the WEC modules have been designed to experience large amplitudes, submergence and water on deck, all standard modules carrying applications on deck, need to be protected. Some of the water reaching the deck level of the standard modules is coming from the pitching WEC modules, see Figure 6-19. It is assumed to be less in reality when the WEC modules are realistically damped.

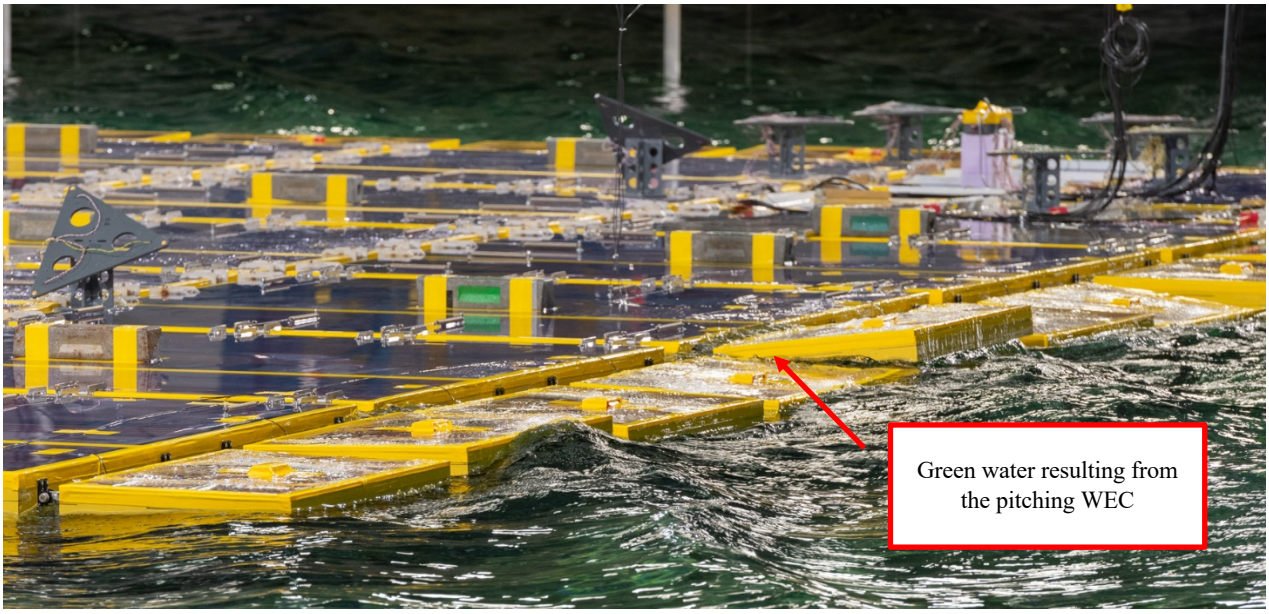

Figure 6-19: Green water on deck of standard modules, partly descending from the pitching WECs

Nevertheless, due to the low freeboard of only 3m, still large amounts of green water are expected. For light spray of breaking waves, stacked containers can contribute as a simple barrier which is one reason why in the integrated Space@Sea island layout the T&I hub faced the most critical wave direction, see Figure 6-20.

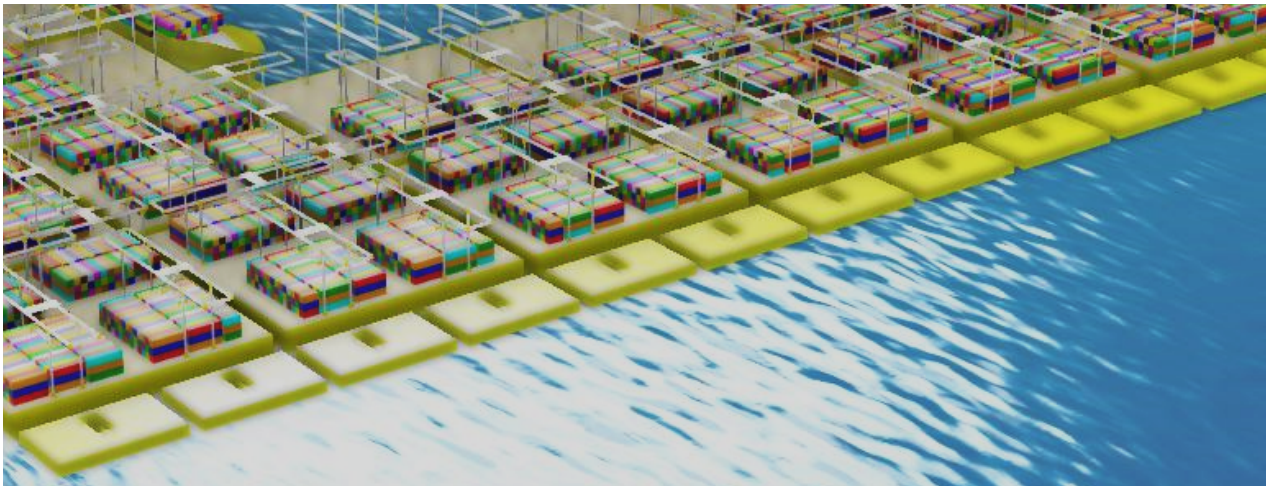

Figure 6-20: Possible contribution of container stacks to protection against green water

For extreme storm sea states, however, the introduction of a proper protection is necessary. Solutions could be:

1. Raising the freeboard.
2. Introducing a separate, floating breakwater in front of the island with the WECs attached to it.
3. Building bulwarks.

or

4. Having only activities on the first row that can easily be replaced or deal with green water in storms.

Within the Space@Sea project, the first two options have been discussed already in the detailed design [6]. Increasing the freeboard would need to be done for all modules in order to maintain a uniform deck level. The introduction of floating breakwaters would ask for immense additional structures as well as mooring or

sand accumulation. According to this, both solutions seem to be economically unrealistic for the island due to significantly rising costs for construction, installation and maintenance.

Hence, if the wave ward modules are carrying applications that need to be protected (so that 4. is not a solution) bulwarks as a local protection against green water waves on deck are proposed, see Figure 6-21. In contrast to higher freeboards or (floating) breakwaters in front of the island, volume, complexity and thus costs of the structure are far lower. As downside of the bulwarks the slightly reduced effective area of the modules could be named, which, however, is supposed to be negligible.

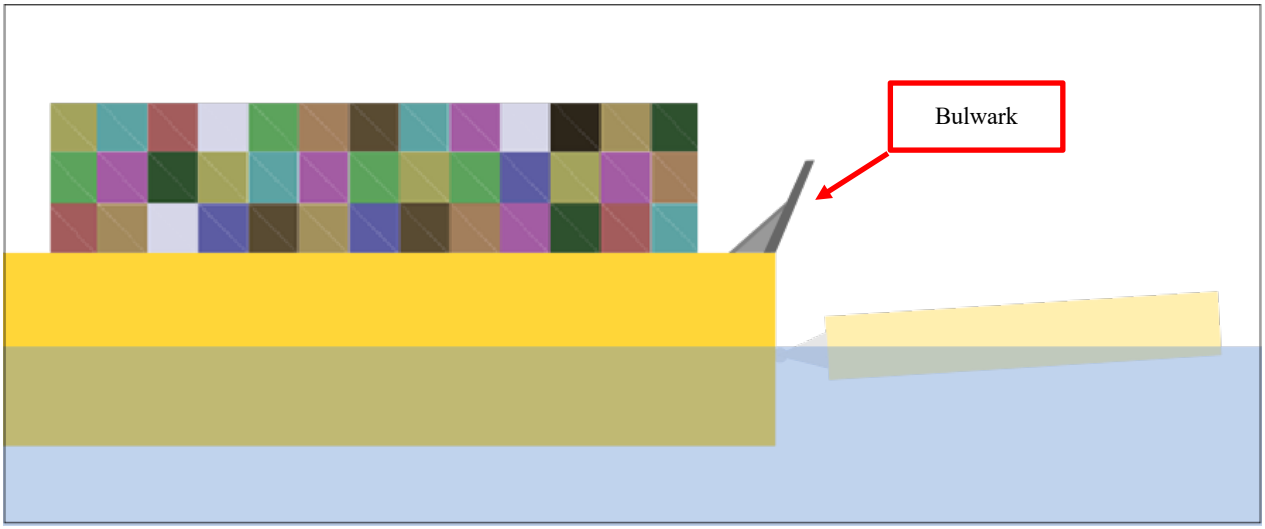

Figure 6-21: Sketched bulwark as protection against green water

In the described tank tests, waves could freely propagate over the surface of the modules. Motions of the modules and loads in connectors and mooring coming from the wave loads acting on the bulwark, were not captured. Thus, the introduction of bulwarks is suggested to be investigated in future. Furthermore, the local slamming loads on the structure should be identified, either by numerical simulations or force panels in model tests. Besides, the WEC modules should be realistically damped. Thereby, the fluid-structure interaction and thus the heights of the passing waves are properly represented and less water is thrown onto the adjacent modules.

6.5 Vessel island interaction tests

The island is intended to provide a sheltered harbour basin for visiting (container) ships. Although no wave height measurements were performed, from photo and video it can be seen that the wave height inside the harbour is significantly reduced. For instance Figure 6-22 shows the phenomena.