LARGE SCALE MODEL TEST ON SAND-FILLED GEOSYSTEMS FOR COASTAL PROTECTION (GEOS)

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Large scale model tests have been performed on a scale 1:5 in the ICTS-CIEM to test the stability of sand-filled geosystems, both tube and bags, and their effect on the morphological evolution of a beach profile. Tube and bags were buried in sand at the upper part of a beach profile with a slope 1:15 in the area where it was transitioning to a beach berm (horizontal flat section). Erosion of the beach during the experiment exposes the tube and bags to direct wave attack. Tests were done under the action of irregular waves with a significant wave height of 2.5 m in prototype, also the effect of two different water levels was considered. Under these conditions the erosion at the seaward side of the tube and bags was limited. Remarkable there was more erosion around the bags. As a consequence of the limited erosion the stability of the structure was never a problem.

1. INTRODUCTION

Flooding, erosion, inundation and extreme weather events affect hundreds of millions of people, important infrastructure, tourism and trade, causing significant human suffering and losses to national economies (World Bank, 2016). The predicted sea level rise and increased storminess in the coming decades is a great threat for the low-lying coastal regions. Existing coastal defences are often insufficient to protect these regions against extreme storms, thus it is mandatory to design and build protective countermeasures. For example, the Coastal Safety Master Plan (Afdeling Kust, 2011) from the Flemish government in Belgium is currently being implemented to provide better protection against extreme storm events. As a counter measure for an extreme storm, it recommends using a combination of a storm wall and beach nourishment. However, the build (and often the rebuild) of more traditional coastal protection measures is showing that many coastal stretches worldwide are still vulnerable to coastal storms and flooding. On top of that are additional restrictions, including costs, and environmental challenges.

Natural and nature-based features can enhance the resilience of coastal areas challenged by sea level rise (Borsje, 2011) and coastal storms (Gedan, 2011). A dynamic coastal protection as dunes is more resilient against sea level rise than fixed structures. This is proven by history: the dune system of the Netherlands and Belgium has adapted itself to the sea level rise in the past although sometimes with considerable erosion and loss of land. The much larger sea level rise that is predicted in the near future, and the need to stabilise the coastline will make human intervention in this natural process necessary. The advantage of a dynamic system is that for example beach nourishments can be continuously adapted to the circumstances (sea level, expected storms). A disadvantage is that significant changes in the coastline may occur in one storm due to erosion. The sand-filled geotextile tubes and bags (further abbreviated as Sand-Filled Elements, SFE) tested in this study have the advantage of a dynamic coast line but limits the erosion of the coast during large storm events because it provides some structural reinforcement. Furthermore, they are easy adaptable to sea level rise by installing new SFE above the first ones without the need to remove the old ones, while a traditional hard structure, normally has to be removed to build a new one.

2. STATE OF THE ART

In recent decades, SFE have been studied intensively (e.g. Oumeraci et al., 2002; Van Steeg and Breteler 2008; Oumeraci and Recio, 2009; das Neves et al., 2015; Van Steeg and Vastenburg 2010; Dassanayake, 2013; and das Neves et al., 2015) as an additional or alternative coastal protection measure. The SFE concept has been tested through physical modelling in both large and small-scale fixed-bed model set-ups and proven its usefulness for coastal protection under certain circumstances. Most of the existing references focus on the stability of the bags; only das Neves (2011) also studied the morphological changes around geosystems, in a small-scale (scale 1:12) movable-bed model set-up. This means that although there are available design guidelines for the stability of these structures (Bezuijen and Vastenburg, 2013), still knowledge gaps can be identified. For instance, *(i)* the sediment transport mechanisms around the SFE; *(ii)* the amount of erosion in the leeside when the system is overtopped; *(iii)* quantitative contribution the SFE for the wave overtopping reduction; and *(iv)* failure mechanisms of the SFE under extreme conditions. Those questions can only be partly answered by using numerical models. There are in general substantial uncertainties and limitations (not only limited to one particular numerical model) for estimating aspects such as (but not limited to) wave-structure interaction and sediment transport, large scale physical model testing was necessary to develop the understanding of coastal processes around the SFE and to predict beach morphological change.

3. AIM OF TESTS

The main objective of the present project is: to evaluate the SFE concept as proposed herein with respect to coastal protection and risk reduction by studying its influence on morphological changes in the coastal zone under storm wave conditions through large scale physical model testing. In addition, physical model results can be further used for the calibration of numerical models. In order to achieve that objective, the following research questions have been defined:

(i) How do nearshore coastal processes (wave transformation, and sediment transport) and wave structure interactions during extreme events differ from those during more usual big storm conditions for situations with and without the SFE?

(ii) How do feedbacks between the hydrodynamics and morphology of natural and nature-based features affect flooding, erosion, and recovery of coastal areas when erosion is limited by the SFE?

(iii) How to conceive a dynamic coastal protection that can easily adapt to climate change in areas experiencing coastal squeeze (i.e. dense urban environment and human infrastructure with sea encroaching land) and vulnerable to coastal erosion and flooding risks?

4. TESTS PERFORMED

Tests were performed in the CIEM wave flume of Barcelona (Universitat Politècnica de Catalunya), a large-scale wave flume of 100 m in length, 3 m in width and 4.5 m in depth.

The initial beach profile (Figure 1) is an idealised bathymetry consisting of a 1:10 approach slope starting at x-coordinate 36 m up to 43 m, measured along the flume from the wave paddle and going positive towards the shoreline. This initial slope is followed by a foreshore 1:25 slope for another 20 m (from x-coordinate 43 m up to 63 m). The beach profile continues for another 14.6 m on a 1:15 slope followed by a beach berm at 2.5 m crest elevation up to the other end of the wave flume opposite to the wave paddle.

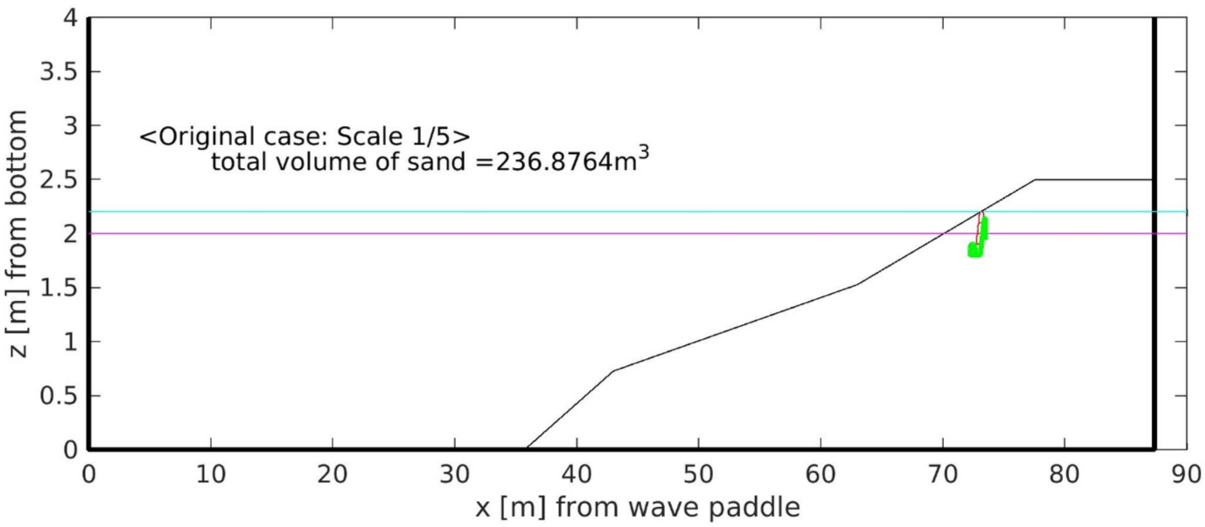


Figure 1. Theoretical initial bed condition. The geobags and geotubes were deployed at the same location (x around 72,42 m where the red and green construction present the geobags buried at that position). In cyan and magenta the SWL to be tested at 2.2 and 2 m

The experimental programme included four different test-series with varying protection and water level conditions (Table 1).

Table 1. Experimental programme and sequence of the tests done during GEOS testing programme (in model dimensions)

Test-series	Protection	SWL (m)	H_s (m)	T_p (s)
1	none (benchmark)	2.2	0.5	4
2	Tube	2.2	0.5	4
3	Tube	2.0	0.5	4
4	Bags	2.2	0.5	4

Test-series were run under a unique wave time series for the whole experimental programme that consisted of an irregular wave train of 1000 waves with significant wave height of 0.5 m and peak wave period of 4 s, both in model dimensions, according to a JONSWAP spectrum (peak enhancement factor of 3.3).

As indicated in Table 1, test-series 1 was performed without protection as a benchmark for the other test-series. Test series 2 and 3 were run with a sand-filled geotextile tube protecting the beach profile, but with two different water levels being 2 and 2.2 m in the model. The last test-series, test-series 4, was run with the bags protecting the beach profile and the highest water level. Tube and bags location are sketched in Figure 2 and picture after construction of the tube and during construction of the bags is shown in Figure 3.

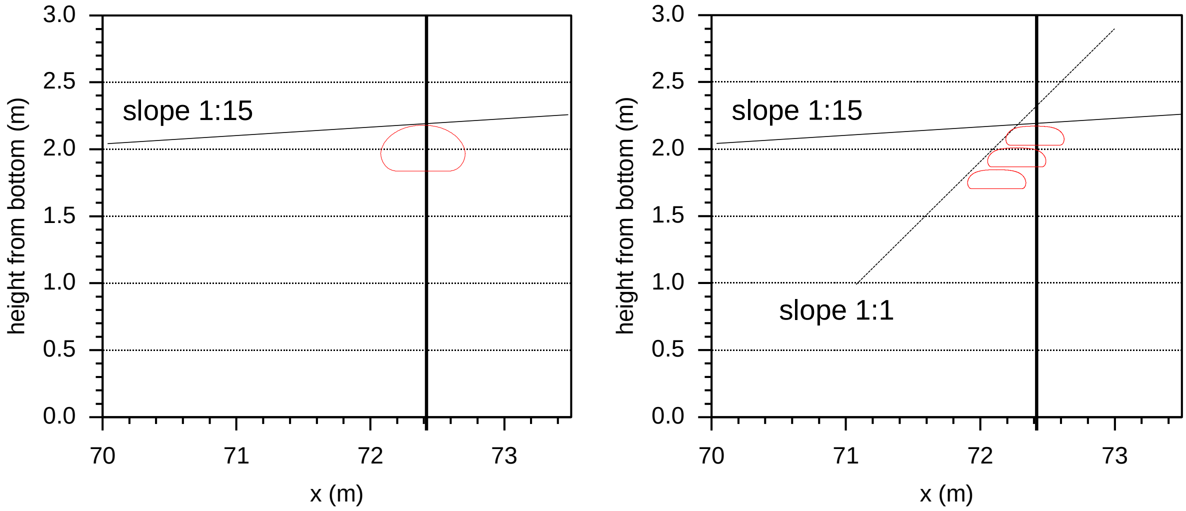
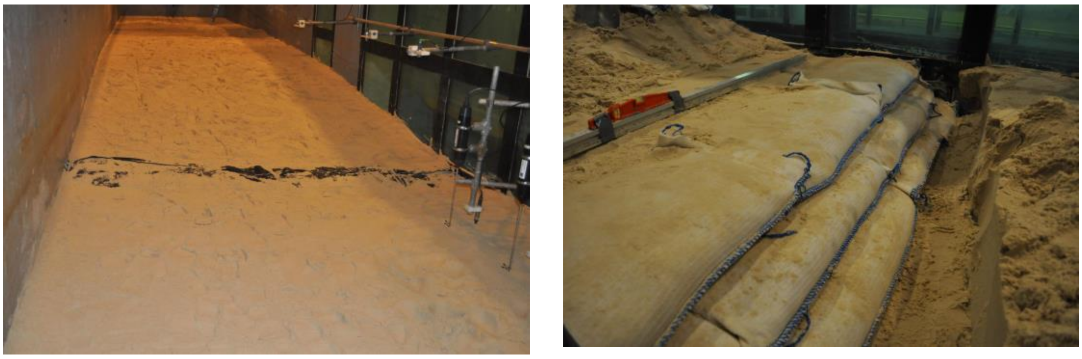


Figure 2. Theoretical position of tube and bags



a)

b)

Figure 3. Images of the a) geotube installed in the beach and b) geobags during installation in the beach

A median sediment grain size of 250 μm was used during the experiments. It should be noted here that this is the sand available at the wave flume, no active choice was made on this. The grain size distribution of the sand was determined in the past and is determined before the tests by sieving. The results are shown in Figure 4. The two recent test samples taken on different locations along the flume evidence almost the same grain size distribution.

The four test-series were produced by 14^{th} repetitions of the same time series (1000 waves with H_s=0.5 m and T_p=4 s), which a duration of around 56 minutes. Before and after each time series, the initial beach profile was recorded for reference. Further measurements of surface elevation, flow velocity and sediment concentrations were recorded and monitored continuously. This paper focus on the morphological evolution of the beach profiles, specifically on the erosion in front of the sand-filled geosystem structures and profile changes within the breaking zone, for the various configurations tested.

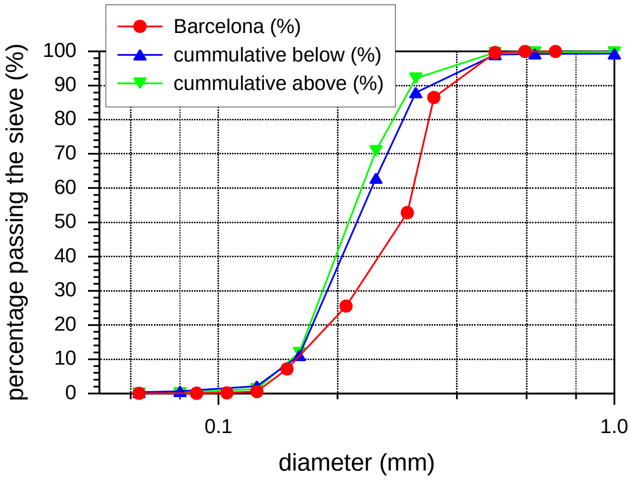


Figure 4. Grain size distribution of the sand used in the tests. The result marked Barcelona was an older determination, and the other two are from just before the tests

5. RESULTS

The developed erosion profile for Test 1, benchmark case, where the beach profile is not protected by SFE, after 14 hours testing is shown in Figure 5. Since there is no well-defined prototype all dimensions are given in model dimensions. The eroded volume is calculated from the upper part of the slope and starts at x-coordinate 86 m from the wave paddle through around 50 m, being at maximum in the area of the profile just above the submerged bar that develops within the profile.

Since the total volume of sand did not change the sum of erosion and accretion should be zero. This is not always the case, which may be justified by some offset in the measurements observed in some test-series. If this was the case, the data is corrected. In some cases, it appears not to be an offset and there may be some compaction of the sand. The difference is clear from the data. In the tests where this happened, the calculated eroded volume does not go back to zero. This may have an influence on the maximum eroded volume calculated from the test results (depending where the compaction occurs).

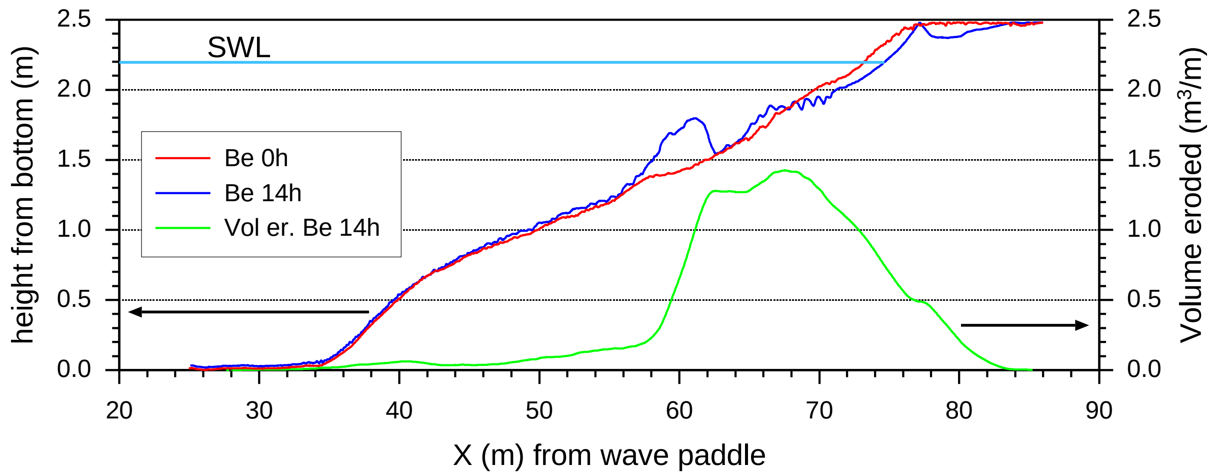


Figure 5. Benchmark test without SFE. Initial slope (Be 0h) and slope after 14 hours of testing (Be 14) and the eroded volume (Vol er. Be 14h)

As described in Van Rijn et al. (2011), the volume of the eroded sediment increases slowly and after 15 hours of testing there is not yet an equilibrium.

The expected influence of the sand-filled geotextile tube was to hold the sand on the landward side of the tube at the expense of more erosion on the seaward side. This appeared hardly the case, see Figure 6 and Figure 7. Only a localised small scour area developed just in front of the tube on the seaward side immediately in front of the geosystem. The erosion at 2 m water level was even less than at 2.2 m water level.

The erosion around the bags and the tubes is compared in Figure 8 and Figure 9. It appeared that the total erosion along the slope is quite comparable. However, there is significantly more scour developing just in front the bags, compared to that area around the tubes. Also, the line of the eroded volume does not reach 0 m^3/m close to the wave paddle. It can be that during the installation of the bags the sand was loosened and was compacted by wave action afterwards.

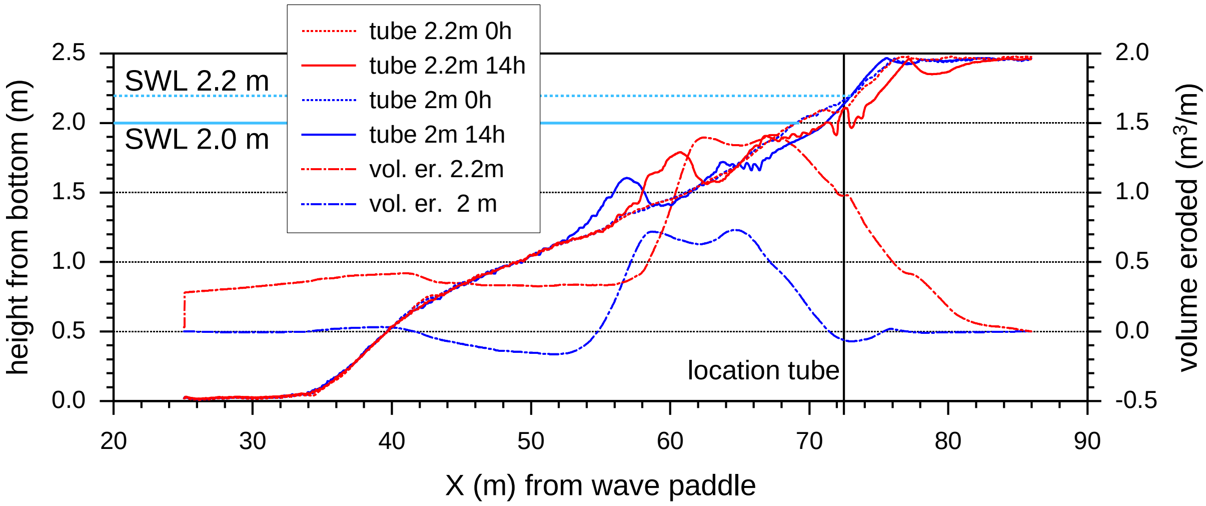


Figure 6. Measured erosion with tube installed in the beach for 2.2 and 2 m water level

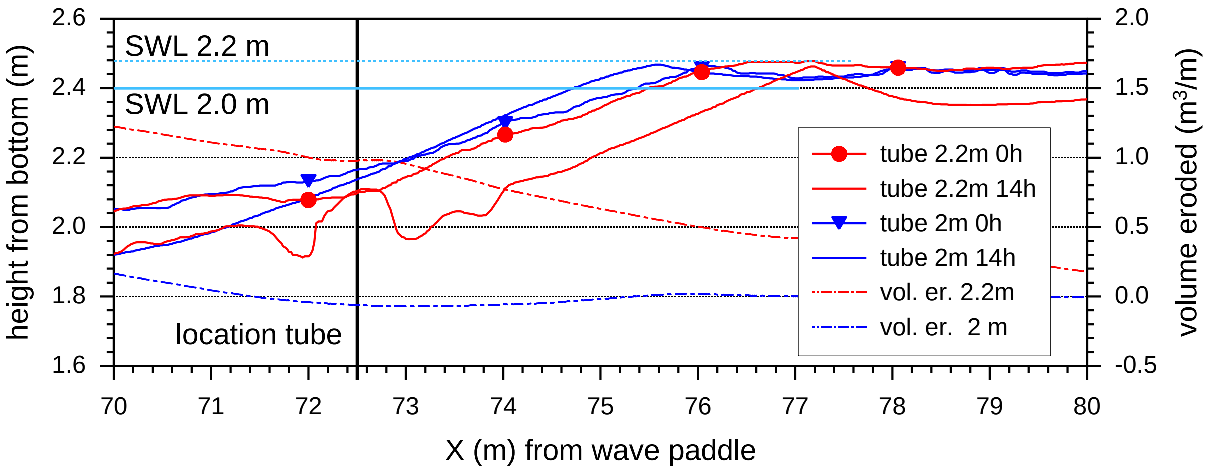


Figure 7. As Figure 6. Upper part of slope

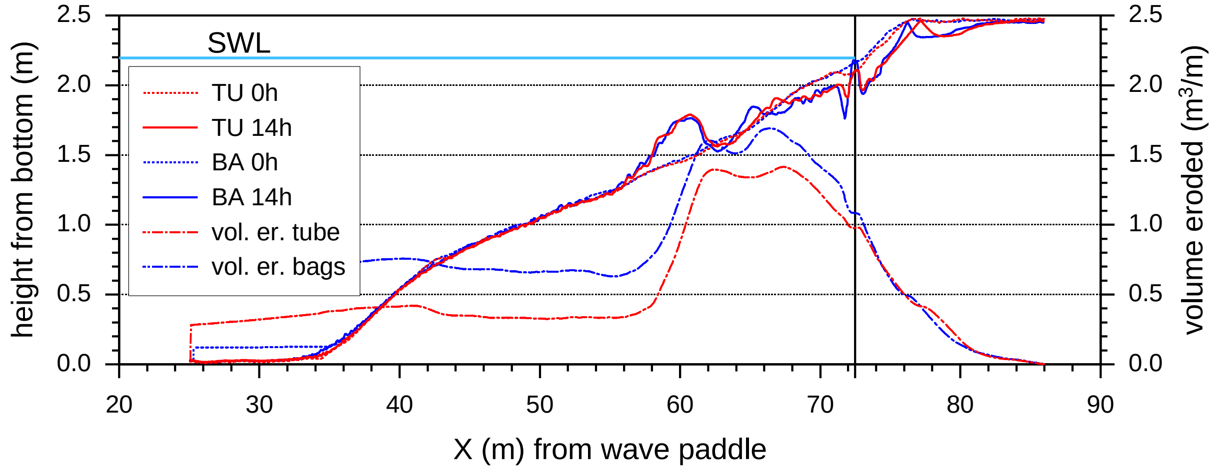


Figure 8. Erosion on beach with tube and bags compared.

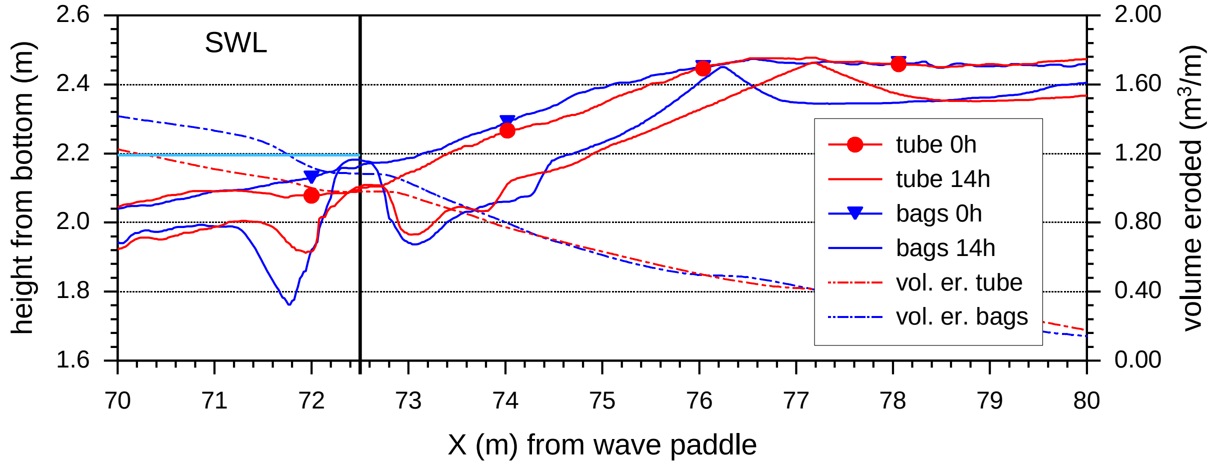


Figure 9. As Figure 9, upper part of slope

5. DISCUSSION AND CONCLUSION

The measured erosion is rather limited in all tests. According to the scaling laws given by Van Rijn (2011), the 250 μm sand in an undistorted 1:5 scale test corresponds to 616 μm in prototype. This is rather course sand, which explains to some extend the limited erosion. The measured erosion with respect to the eroded volume is in agreement with XBeach simulations. However, the submerged bar that develops within the breaking zone along the beach profile has a shape that is completely different from that predicted with XBeach,

The limited influence of the tubes and the bags on the erosion results, means that these elements can be applied as a dune toe protection, although it is advisable to check the results for circumstances where more erosion can be expected (for a situation with, scaled to prototype, smaller grains). Remarkable was that there was hardly any deformation for both the tube and bag structure during the tests, which indicates that these structures are internally sufficiently stable under wave heights of 0.5 m and the position on the beach tested here.

The difference in erosion around the structure between the tube and the bag is a remarkable result. This indicate that small differences in the structure already have quite an influence on the erosion results. This result needs further investigation, since this result can be rather important for necessary maintenance on these structures.

The tests indicate that a SFE dune toe protection is feasible. However, the tests described here are only a first indication. As mentioned, the erosion was limited, also the influence of tide and longshore current was not tested. However, the stability of the SFE structures and that, within the limits of testing, the influence of the water level is limited are promising results.

ACKNOWLEDGEMENT

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