DYNAMIC COBBLE BEACHES AS SEA DEFENCE

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The study presented here focussed on fundamental aspects of revetments with dynamic rock slopes and gravel beaches. Obviously, the response of gravel beaches and cobble beaches depend on parameters such as the wave height and the stone size. Here, other parameters such as the permeability of the subsoil and the influence of sand in the pores of gravel have been studied. This study is based on laboratory investigations in three types of facilities: A wave flume for small-scale tests, a wave flume for large-scale tests at a close-to-prototype scale, and a wave basin for 3D tests. The results also provide insight into the magnitude of scale effects.

Keywords: cobble beaches, gravel beaches, rock slopes, sea defences, scale effects, laboratory tests.

1. Introduction

Coastal defence systems often consist of dunes and dikes, where sandy dunes are dynamic systems and dikes are static sea defence structures. For dunes it is important to predict the amount of dune erosion during severe storms (see *e.g.* Van Gent *et al*, 2008). For dikes several failure mechanisms exist, but the dikes are not allowed to undergo significant changes under storm conditions. In harbours, usually the breakwaters are also designed as static structures for which no or very limited movement of material is considered acceptable. However, a berm breakwater is a type of breakwater that is allowed to undergo some reshaping under severe storm conditions. Of course for berm breakwaters the prediction of the amount of reshaping is essential (see *e.g.* Van der Meer, 1988, Van Gent, 1995-a,b, PIANC, 2003). Between the large (rock) material that is applied in berm breakwaters and the small material in sandy dunes, other dynamic slopes consist of gravel or cobbles. The study presented here focussed on aspects that are relevant for coastal revetments that consist of gravel or cobbles.

Figure 1. Applied small-scale (left) and large-scale (middle) wave flumes and multi-directional wave basin (right).

The response of gravel beaches and cobble beaches depend on a series of parameters (wave height, wave period, number of waves, stone diameter, initial slope, *etc*). These dependencies have been described by Van der Meer (1988). Kao and Hall (1990) studied, amongst other aspects, the influence of a wide grading. In Van Gent (1995) the response of gravel beaches was modelled by simulating processes numerically; in Van Gent (1996) stone segregation, the influence of a narrow or wide grading, and the influence of seawalls on the response of gravel beaches were modelled numerically. The study described here was performed to provide insight into the following aspects:

1) How does the permeability of the subsoil affect the dynamic response of gravel/cobble beaches?
2) If the pores of the gravel/cobbles are filled with sand, how does this affect the dynamic response?
3) Is the dynamic response of gravel/cobbles of which the pores are filled with sand, after the gravel/cobbles have been placed, significantly different from the response of beaches where sand and gravel/cobbles are mixed before placement (thus without grain-structure of gravel/cobbles)?
4) What is the magnitude of scale effects?
5) In the case of perpendicular wave attack, how large are the variations between profiles in various cross-sections?
6) Does directional spreading significantly increase these variations (item 5)?

To provide insight into these aspects laboratory investigations are performed in three wave facilities of Deltares | Delft Hydraulics: A wave flume for small-scale tests, a wave flume for large-scale tests, and a multi-directional wave basin (see Figure 1). The tests represent gravel beaches and cobble beaches. The large-scale tests can be seen as a scale test of about 1:4 to 1:10 for cobbles while these tests are 1:1 tests for gravel beaches.

The wave flume applied for the small-scale tests has a length of 55m, a width of 1m and a height of 1.2m. The large-scale tests were performed in the Delta Flume. This flume has an effective length, width and height of 225m, 5m and 7m respectively. These wave facilities of Deltares | Delft Hydraulics are equipped with wave generators with Active Reflection Compensation to prevent reflected waves to re-reflect into the flume, and second-order wave steering. For the large-scale tests waves up to H_s=1.35m were generated and for the small-scale tests waves up to H_s=0.24m.

2. Small-scale wave flume tests

Test set-up

Small-scale tests were performed to provide insight into all research aspects mentioned in the introduction. Five test series (S1-S5) are presented here. Table 1 provides an overview. For all tests an initial slope of 1:8 was used. The length of the slope was such that no overtopping could occur. A layer of gravel with a thickness of 0.18m was placed on top of an impermeable underlayer (see Figure 2), except for Series S5 where the structure was homogeneous. The layer thickness was such that it has not been completely eroded in any of the test series (the underlayer has not been exposed). In the small-scale tests the material to characterise gravel consisted of crushed stones with d_{50}=3.6mm (d_{85}/d_{15}=1.8; ρ_s=2593kg/m^3). The sand used in these tests can be characterised by d_{50}=125μm (d_{85}/d_{15}=1.8). One wave condition was tested: H_s=0.24m and T_p=2.16s (s_p=0.033), using a standard Jonswap spectrum. This leads to $H_s/\Delta D_{n50}$=50 for the applied toplayer. The water depth in front of the structure was 0.75m.

Table 1. Test programme small-scale tests.

Series	Description	Underlayer		Sand			
				sand in pores			
		impermeable	homogeneous	0%	20%	max.	mixed
S1	No sand in pores	X		X			
S2	Pores partly filled with sand	X			X		
S3	Completely filled pores	X				X	
S4	Mixed material	X					X
S5	Homogeneous, no sand in pores		X	X			

Test programme

Series S1 was performed for the basic configuration without sand in the pores of the gravel (*i.e.* the toplayer consisted of gravel without sand). The toplayer for Series S2 was constructed identical to Series S1, but after that, a layer of sand was placed on top of the gravel. By sprinkling water on top of the sand, the sand infiltrated into the pores of the gravel. This way the sand did not affect the structure of the gravel material. The amount of sand is such that about 40% of the pores are filled with sand, using a porosity of n=0.4 for the gravel without sand. In Series S3 the permeability of the gravel was further reduced by using a maximum amount of sand, such that all pores that could be filled with sand would be filled; this is estimated at about 85% of the pores. In Series S4 the gravel and sand was mechanically mixed (same amount as for Series S3) before placing it in the flume. Series S5 consisted of a homogeneous structure such that a comparison can be made with the structure with an impermeable underlayer (S1) and, due to the presence of sand, a structure with an even lower permeability (for instance Series S3).

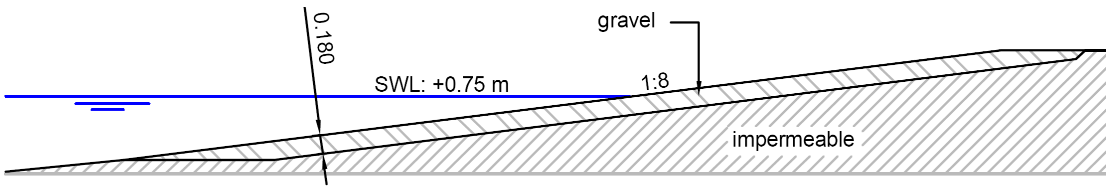

Figure 2. Model set-up in small-scale tests (for Series S1-S4).

Before and after each test run, nine longitudinal cross-shore transects were measured with a mechanical bed profile follower. Profiles were also measured at several temporary test interruptions to provide insight into the development of the profile as a function of the number of waves. The analysis is based on the bed profiles that are the average of the nine cross-shore transects. The differences between the individual profiles are small.

Response of gravel/cobble beach with and without sand in pores

Figure 3 shows the response of the beach profile in time for Series S1, after approximately 1000, 2000, 3000, 4000 and 5000 waves. Each of these individual parts consisted of the same wave train of approximately 1000 waves with the same significant wave height and peak wave period. This figure shows that above the water level there is only accretion while the erosion takes place below the water level. The following observations were made:

- The height of the beach crest increases with an increasing number of waves (in this test up to about 1.5 H_s above the water level after 5000 waves).
- The position of the beach crest moves somewhat seaward in time; thus the distance of the crest compared to the position of the original waterline decreases with an increasing number of waves.
- The point where the rear side reaches the original profile is constant. This position is determined by the initial run-up length; the distance of this run-up point does not depend on the number of waves.
- The waterline moves seaward in time.
- There is a transition point along the profile where there is erosion below this point and accretion above this point. In the final situation after 5000 waves this point is approximately 0.5 H_s below the water level.
- Below the water level there are initially two parts where erosion occurs. The most significant one develops at the position where the original depth is about 1 to 1.5 H_s . This is the point where the scour depth reaches its maximum. This erosion develops gradually. The other erosion area is in somewhat shallower water and reaches its maximum in the initial phase while in the final situation the amount of erosion in this section is reduced. This erosion is in a section with high mobility and the maximum erosion depth can change within in a few waves.

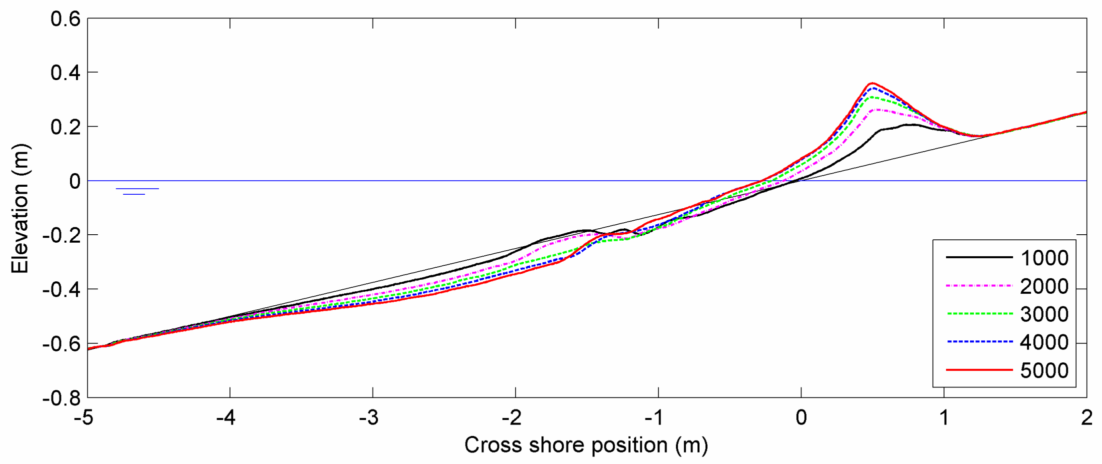

Figure 3. Small-scale tests: Development in time (no sand in pores).

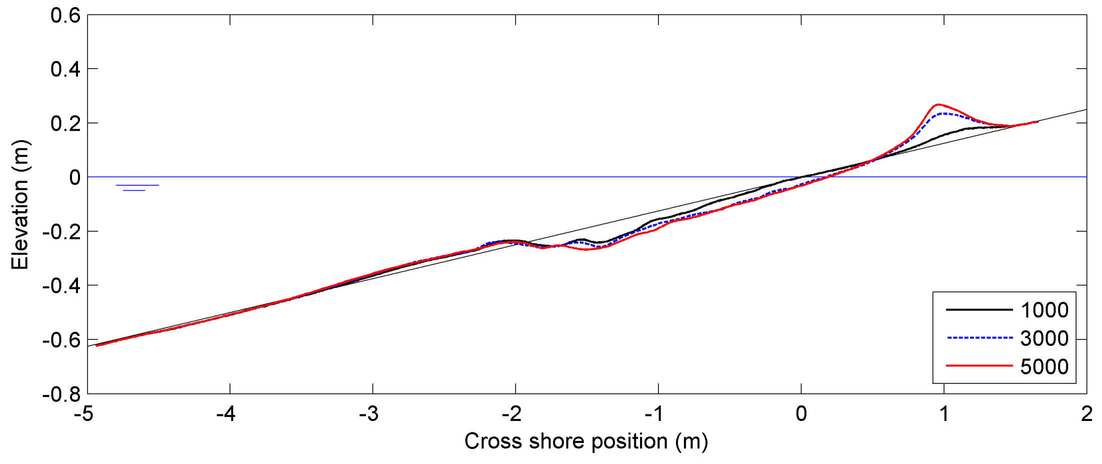

Figure 4. Small-scale tests: Development in time (with sand in pores).

Figure 4 shows the response of the beach profile in time for Series S3, where the pores were filled with a maximum amount of sand. Again the crest height increases in time, the position of the crest moves seaward, and the point where the rear side reaches the original profile is constant.

Figure 5 shows the test results for three test series, one where there is no sand in the pores (S1), one where the pores are partly filled with sand (S2), and one where the amount of sand in the pores is maximal (S3). Figure 5 (profiles after 5000 waves) clearly shows the following:

- The amount of erosion and accretion is the most for the situation without sand in the pores and the lowest for the beach with the highest amount of sand in the pores.
- Adding sand leads to a lower beach crest. This crest is positioned further landward. It is likely that this is caused by a higher run-up level, which is due to a lower permeability of the toplayer.
- The maximum erosion depth (compared to the initial slope) is hardly influenced by the amount of sand in the pores. The position where the maximum erosion depth occurs varies; for the beach with the largest amount of sand this point of maximum erosion is in shallower water than for the other two configurations.

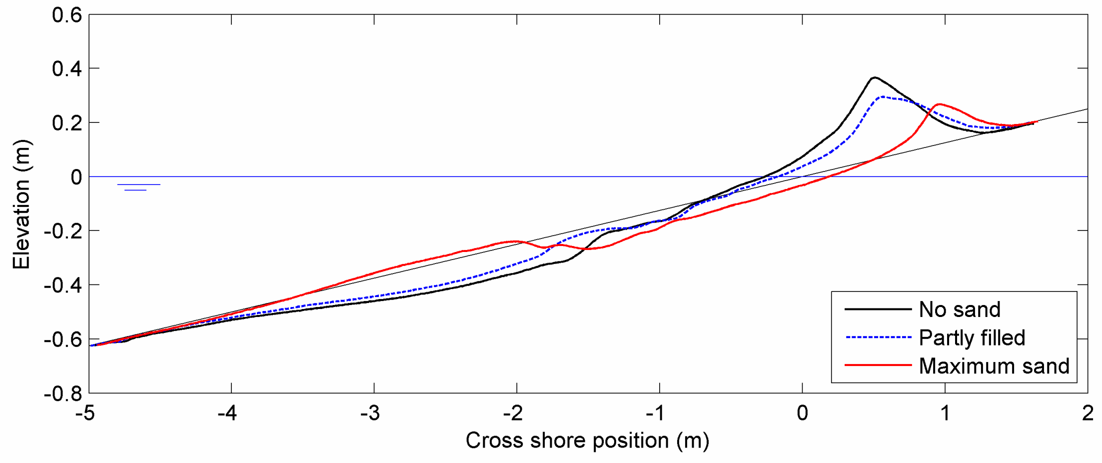

Figure 5. Small-scale tests: Comparison of profiles with and without sand in pores.

Influence of "grain-structure"

Figure 6 shows a comparison between a beach where the sand was added later into the pores of the gravel (S3) such that the stones are against each other (with “grain structure”) and a ‘mixed beach’ where the sand and gravel were mixed before it was placed in the toplayer (S4). This figure shows the following:

- For the mixed beach the accretion above the water level is larger.
- The amount of erosion below water is larger for the mixed beach and the part where erosion takes place is much wider and also takes place in deeper water.
- The maximum depth of erosion compared to the original profile is hardly different for both toplayers.

She *et al* (2007) also compared mixed beaches with gravel beaches without sand. Some of the conclusions are similar (*e.g.* “less onshore transport for mixed beaches compared to gravel without sand”), but some are different (*e.g.* “more offshore transport for mixed beaches”).

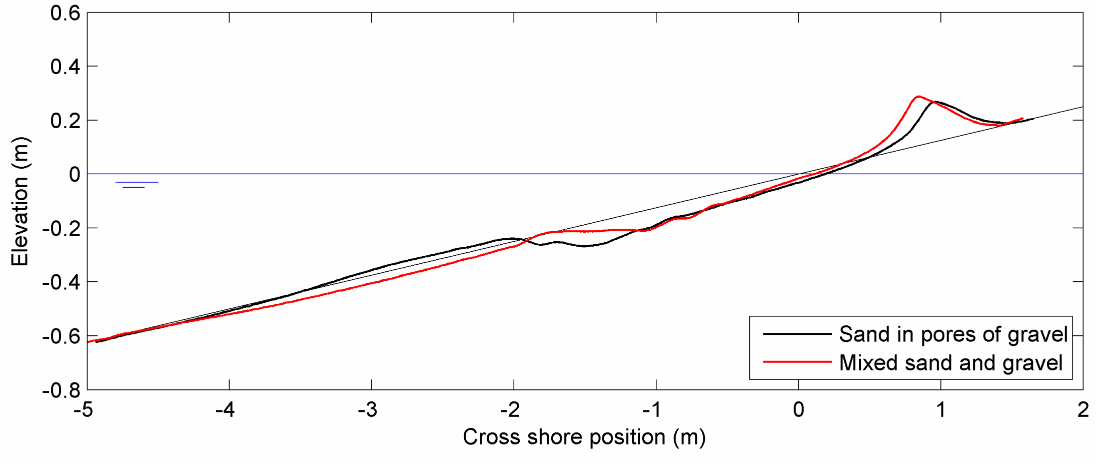

Figure 6. Small-scale tests: Comparison between profiles with sand in pores and a mixed beach.

Influence of permeability of the sub-soil

Figure 7 shows the test results for three test series with 1:8 beaches with a different permeability; one beach was homogeneous, thus without an impermeable core (S5), one with an impermeable core but with a permeable toplayer without sand in the pores (S1), and one where the amount of sand in the pores is maximal (S3). Figure 7 (profiles after 5000 waves) shows the following:

- The amount of erosion and accretion is the most for the homogeneous structure; the maximum erosion depth and the highest beach crest occur for the homogeneous structure (for steeper initial slopes this may be different); the average slope in the region between the beach crest and the maximum erosion depth is the steepest for the most permeable structure.
- The influence of sand in the pores seems to be larger than the influence of the permeability of the core; the differences between Series S1 and S3 (without and with sand in the pores, respectively) are larger than the differences between Series S1 and S5 (with and without an impermeable core).

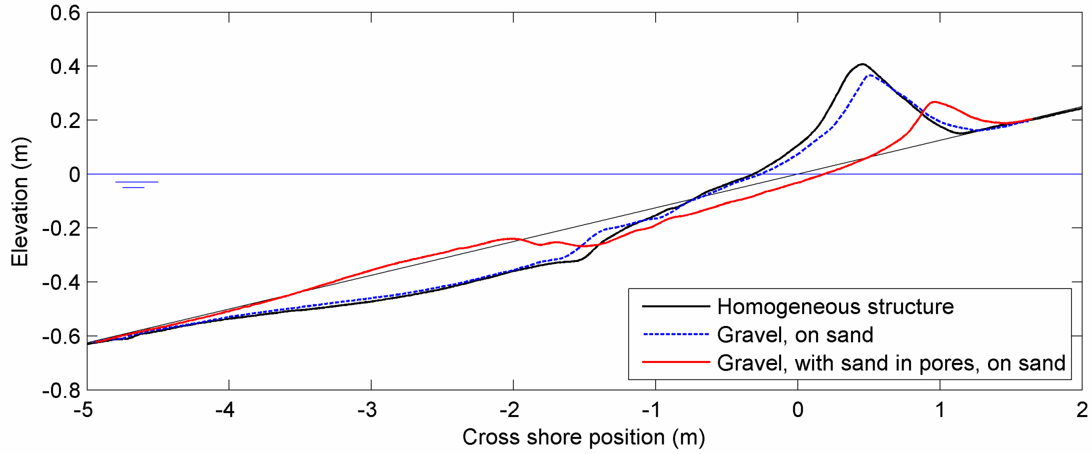

Figure 7. Small-scale tests: Influence of permeability.

3. Large-scale wave flume tests

Test set-up and test programme

Large-scale tests were performed to provide insight into the second and fourth aspects mentioned in the introduction: If the pores of the gravel/cobbles are filled with sand, how does this affect the dynamic response, and what is the magnitude of scale effects? Two test series (L1 and L2) are presented here. Series L1 was performed without sand in the pores of the gravel/cobbles. Series L2 was performed with sand in the pores of the gravel. Table 2 provides an overview of these test series. Again an initial slope of 1:8 was used. The length of the slope was such that no overtopping could occur. A layer of gravel with a thickness of 0.75m was placed on top of an impermeable underlayer (see Figure 8). This impermeable underlayer consisted of sand. The toplayer consisted of crushed gravel with d_{50}=17.4mm (d_{85}/d_{15}=3.6; ρ_s=2638kg/m^3). The sand used in these tests can be characterised by d_{50}=214 µm (d_{90}/d_{10}=2.2). Only one wave condition was tested: H_s=1.35m and T_p=5.0s (s_p=0.034), using a standard Jonswap spectrum. This leads to $H_s/\Delta D_{n50}$=56 for the applied toplayer. The water depth at the wave board was 4.125m.

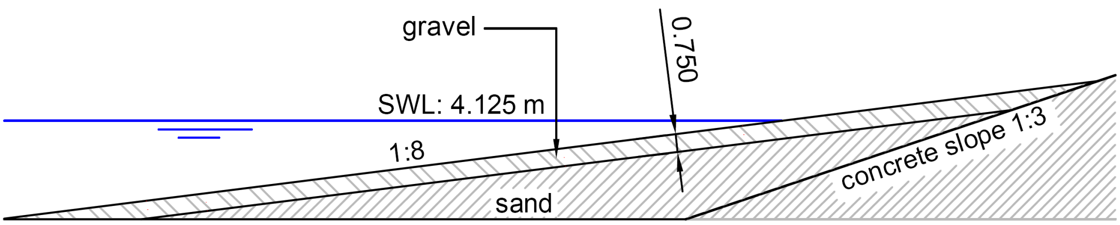

Figure 8. Large-scale tests: Model set-up.

The large-scale tests are approximately a factor 5.5 larger than the small-scale tests, although not all parameters are exactly scaled with this factor: The value for $H_s/\Delta D_{n50}$ is 10% larger in the large-scale tests. The wave height is a factor 5.6 larger than in the small-scale tests. The value for ΔD_{n50} is a factor five larger than in the small-scale tests. The grading is much wider in the large-scale tests. The layer thickness is relatively thin in the large-scale tests. The wave steepness is nearly the same. Of these parameters the wave height and the wave steepness are considered as the most important for the response of beaches. Therefore, the differences are considered acceptable to compare the results of the large-scale tests and the small-scale tests.

Series L1 was performed without sand in the pores. The toplayer for Series L2 was constructed identical to Series L1, but after that, a layer of sand was placed on top of the gravel. By sprinkling water on top of the sand, the sand infiltrated into the pores of the gravel. This way the sand did not affect the structure of the gravel material. In this test series a maximum amount of sand was used, such that all pores that could be filled would be filled; this is estimated at about 75% of the pores (using a porosity of n=0.33). The ratio between the diameters of gravel and sand (approximately 80) is much larger than for the small-scale tests (approximately 30).

Table 2. Test programme large-scale tests.				
Series	Description	Underlayer	Sand in pores	
		Impermeable	0%	max.
L1	No sand in pores	X	X	
L2	Completely filled pores	X		X

Before and after each test run, five longitudinal cross-shore transects were measured with a mechanical bed profile follower. Profiles were also measured at several temporary test interruptions to provide insight into the development of the profile as a function of the number of waves. Each of these test series consisted of at least 17000 waves, which is approximately 20 hours in the model. The analysis is based on the bed profiles that are the average of the five cross-shore transects. The differences between the individual profiles are small although slightly larger than in the small-scale tests.

Response of gravel/cobble beach without and without sand in pores

Figure 9 shows the test results for both test series, one where there is no sand in the pores (L1) and one where the amount of sand in the pores is maximal (L2). Figure 9 (profiles after 17000 waves) shows the following:

- There are clear differences between the two profiles. The amount of erosion and accretion is the most for the situation without sand in the pores and the lowest for the beach with sand in the pores; the net transport of material is much lower for the beach with sand in the pores of the gravel.
- Adding sand leads to a lower beach crest. This crest is positioned further landward. It is likely that this is caused by a higher run-up level, which is due to a lower permeability of the toplayer.
- The maximum erosion depth (compared to the initial slope) is less for the toplayer with sand in the pores. The position where the maximum erosion depth occurs is in deeper water for the toplayer with sand in the pores.
- The waterline is not varying for the toplayer with sand in the pores while it moves seaward for the toplayer without sand.
- The first two trends described here were also observed in the small-scale tests, the last two are different.

Comparison of small-scale tests and large-scale tests

Figure 10 shows a comparison between profiles from the large-scale tests (L1) and a profile from a corresponding small-scale test (S1), both without sand in the pores of the gravel. The small-scale profile is Froude-scaled with a factor 5.5 to the large scale. The profile from the small-scale test is after 5000 waves. The profiles from the large-scale test are after 5000 waves and after 17000 waves. The large-scale profile after 17000 waves and the small-scale profile after 5000 waves are both at a point in time where the profile is reshaping at a very low rate. Figure 10 shows the following:

- The small-scale test shows more erosion and accretion (and thus more upward transport) than the large-scale test, even if the comparison is made with a profile after a significantly larger number of waves (17000 versus 5000). The profiles after 5000 waves show that the total amount of accretion and the amount of erosion are roughly a factor 1.5 larger in the small-scale tests; after 5000 waves also the maximum scour depth (compared to initial situation) is roughly a factor two larger in the small-scale tests.
- In the small-scale test the beach crest is higher and more seaward than in the large-scale test. Comparing the profiles after 5000 waves shows that the beach crest, if compared to the initial profile, is roughly a factor two larger in the small-scale tests.
- The waterline moves seaward in both the large and the small-scale test, and the differences are small.

Figure 11 shows a comparison between profiles from the large-scale tests (L2) and a profile from a corresponding small-scale test (S3), both with sand in the pores of the gravel. The small-scale profile is Froude-scaled with a factor 5.5 to the large scale. The profile from the small-scale test is after 5000 waves. The profiles from the large-scale test are after 5000 waves and after 17000 waves. This comparison shows the following:

- The small-scale test shows more erosion and accretion (and thus more upward transport) than the large-scale test if the comparison is made between profiles after the same amount of waves (5000). After 17000 waves in the large-scale test, the beach crest is more or less of a similar magnitude and at a similar position, as after 5000 waves in the small-scale test.
- Below the water level the large-scale test shows a section with accretion; the small-scale test shows also some accretion in this section but much less.
- The small-scale test shows a maximum erosion depth at a position where the large-scale tests do not show important erosion.
- In general it can be concluded that the sections with accretion show some similarities but that the sections with erosion are significantly different.

From the large-scale tests it can be concluded that if the pores of the gravel are filled with sand, the dynamic response reduces. This results in a lower beach crest and less erosion below water. For revetments with gravel/cobbles with sand in the pores, a lower beach crest may therefore result in more wave overtopping.

From the comparison between small-scale tests and large-scale tests it can be concluded that small-scale tests provide valuable qualitative information for situations where the pores of gravel/cobbles are not filled with sand. However, the performed small-scale tests overestimate the amount of accretion and erosion (and may underestimate the amount of wave overtopping due to a too high beach crest). If the pores of the cobbles/gravel are filled with sand, the model and scale-effects are larger; above water (where accretion occurs) there are some similarities, but below water (where erosion occurs) differences are large.

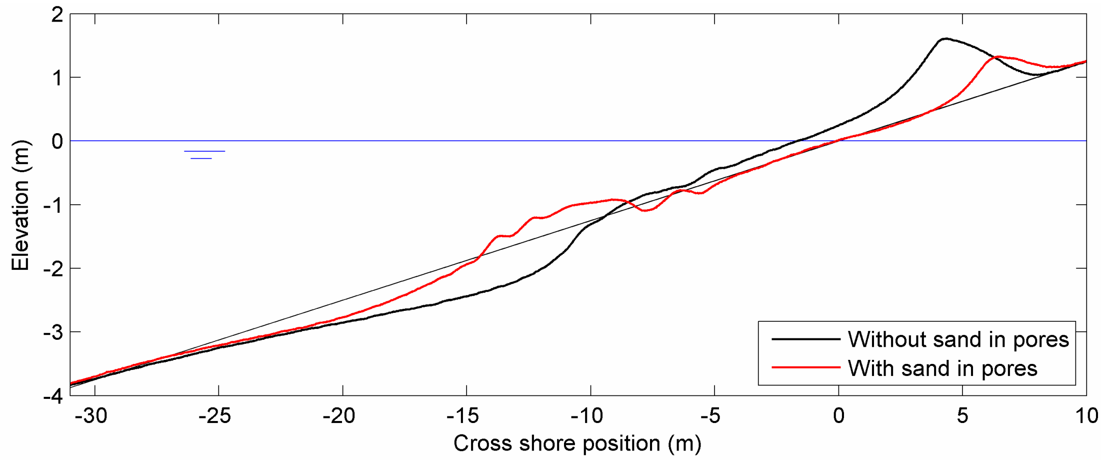

Figure 9. Large-scale tests: Comparison of profiles with and without sand in pores.

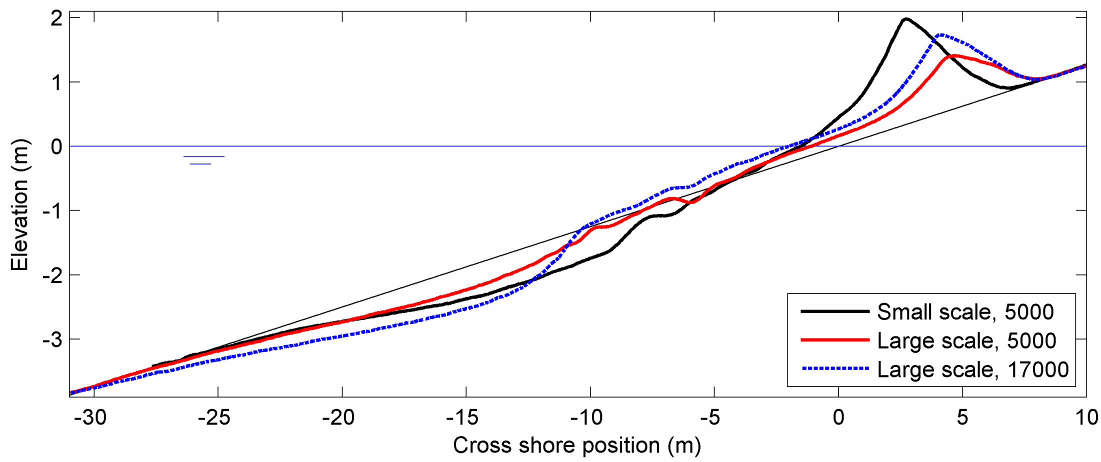

Figure 10. Comparison between large-scale and small-scale tests (no sand in pores).

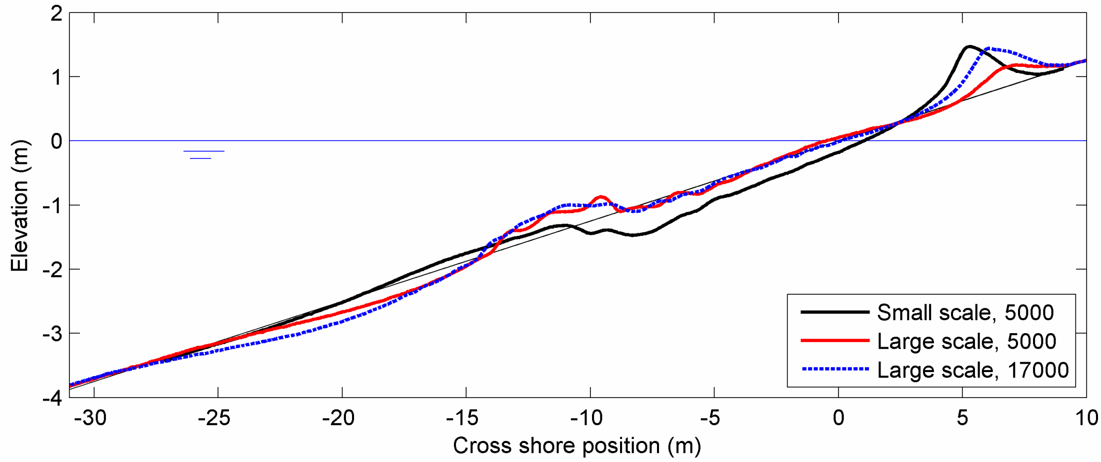

Figure 11. Comparison between large-scale and small-scale tests (with sand in pores).

4. Wave basin tests

Small-scale tests were also performed in a wave basin to provide insight into some 3D effects. In the small-scale tests and the large-scale tests in wave flumes the differences between individual profiles compared to the average profile were rather limited. The test series described here were performed to analyse whether these variations are significantly larger for a beach that is much wider. In the wave flume tests the width was 1m in the small-scale tests and 5m in the large-scale tests. Taking the scale between these two types of tests into account (5.5), the non-dimensional width of the flume is similar for both types of tests: about 300 times the stone diameter and about four times the wave height. The wave basin tests were performed on a scale of about 1:2 compared to the small-scale tests in a wave flume and 1:11 compared to the large-scale tests. The width of the beach was 26.4m, leading to a width of the beach that is about 13000 times the gravel diameter and more than 200 times the wave height. The wave height was H_s=0.12m and the peak wave period was T_p=1.5s (s_p=0.034). The water depth at the wave board was 0.375m. The material to characterise gravel had a diameter of d_{50}=2.0mm (d_{85}/d_{15}=2.1; ρ_s=3002kg/m^3). It should be noted that the density is much higher than the material applied in the described wave flume tests. This leads to $H_s/\Delta D_{n50}$=35 for the applied toplayer. The thickness of the toplayer was 0.09m. Underneath an impermeable slope was constructed, again with a slope of 1:8. No sand was added to the toplayer. Two test series were performed, one with long-crested waves (3D-1) and one with short-crested waves (3D-2). Both test series were performed with a maximum of 15000 waves.

The described large-scale tests are approximately a factor 11 larger than these small-scale tests, although several parameters are not scaled with this factor: The wave height is a factor 11 larger than in the small-scale tests. The value for ΔD_{n50} is a factor seven larger than in the small-scale tests. The value for $H_s/\Delta D_{n50}$ is a factor 1.6 larger in the small-scale tests. The layer thickness is a factor eight larger than in the small-scale tests. The grading is a factor 1.7 wider than in the small-scale tests. The wave steepness is the same.

Before and after each test run, five longitudinal cross-shore transects were measured with a mechanical bed profile follower. Profiles were also measured at several temporary test interruptions to provide insight into the development of the profile as a function of the number of waves.

Figure 12 shows the average profile after 15000 waves for the test with long-crested waves (3D-1) together with the largest differences of individual profiles (*i.e.* envelope). For the tested condition the differences between the individual profiles are small although slightly larger than in the wave flume tests.

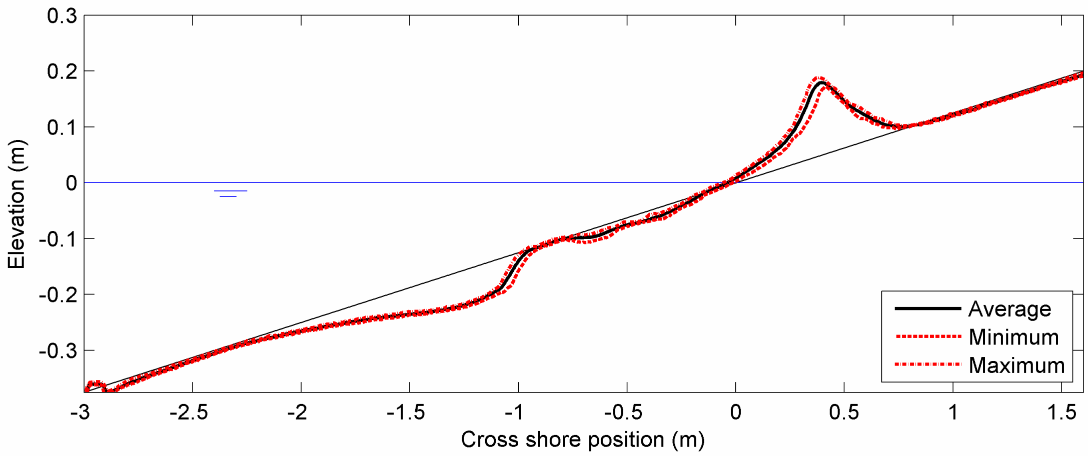

Figure 12. 3D tests: Differences between individually measured and average profile (long-crested waves).

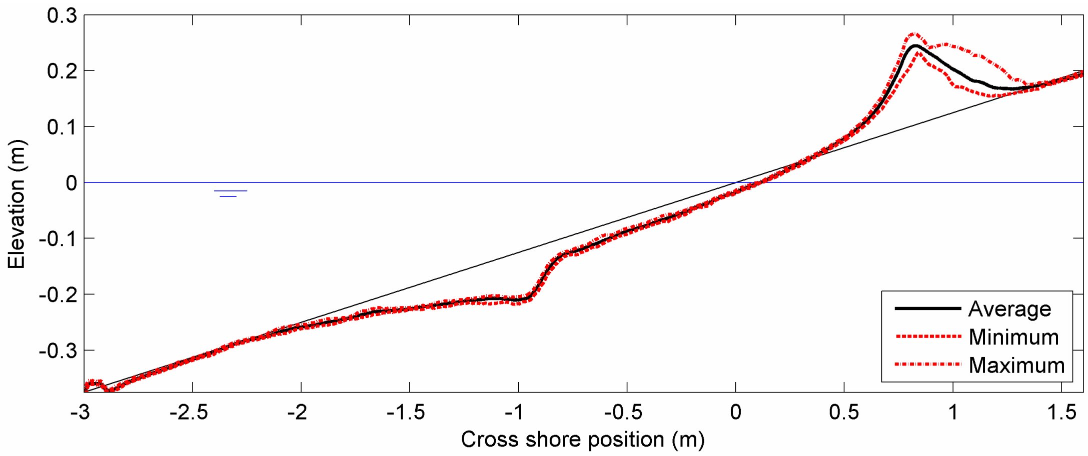

Figure 13. 3D tests: Differences between individually measured and average profile (short-crested waves).

To analyse whether other aspects affect the differences between individual profiles a second test series was performed. This test series was performed with short-crested waves instead of long-crested wave. Except from this difference, in this second test series also a different wave energy spectrum was applied; this wave energy spectrum was a combination of the wave spectrum applied in Series 3D-1 with a peak wave period of T_p=1.5s and a wave spectrum with swell (low-frequency energy) with a peak wave period of T_p=8s. The total energy was nearly the same as for Series 3D-1 but now 20% of the total energy was in the swell component.

Figure 13 shows the average profile after 15000 waves for the test with short-crested waves (3D-2) together with the largest differences of individual profiles (*i.e.* envelop). The differences between the individual profiles are larger for the short-crested waves with low-frequency energy than for the long-crested waves. The most significant differences are at the rear side of the beach crest while below water the differences between the individual profiles are very small. Because the differences between individual profiles are small, the mean profiles can be considered as a rather good representation of the test results.

Figure 14 shows a comparison between the mean profiles for the test with long-crested waves (3D-1) and the test with short-crested waves (3D-2), both after 15000 waves. The differences are large. The beach crest is much more pronounced for the test with short-crested waves and a significant portion of low-frequency energy (3D-2). Also the amount of erosion is larger for the test with short-crested waves and a significant portion of low-frequency energy. From the test results it cannot be concluded whether the differences are due to long-crested waves versus short-crested waves, due to a different amount of low-frequency energy, or due a combination of both. Low-frequency energy temporarily leads to a different water level. Therefore, it is expected that the different position of the beach crest is (at least partly) due to differences in low-frequency energy.

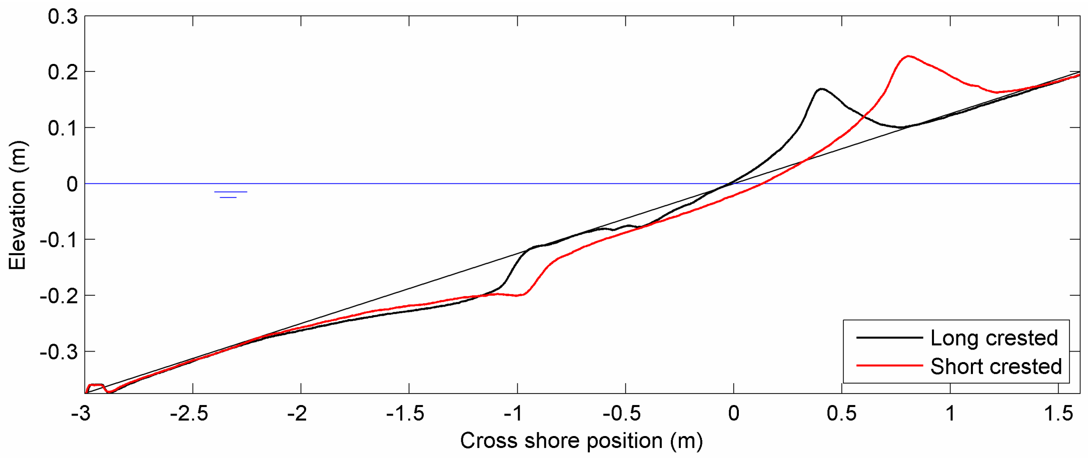

Figure 14. 3D tests: Comparison of profiles with long-crested and short-crested waves.

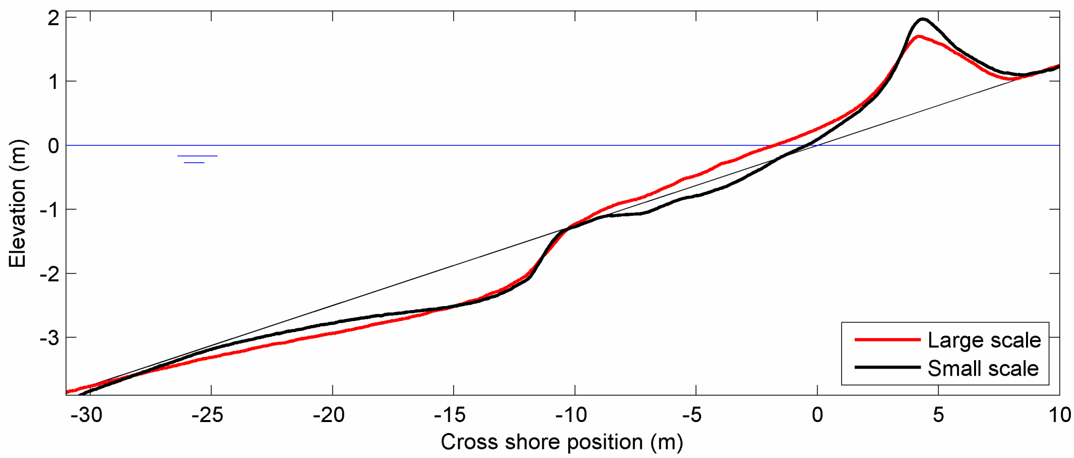

Figure 15. Comparison between large-scale test and small-scale test.

As mentioned before, these 3D tests are not an exact scale model of the large-scale tests ($H_s/\Delta D_{n50}$ is a factor 1.6 larger in the small-scale tests). Nevertheless, a comparison is made between the small-scale test and the large-scale test. Figure 15 shows a comparison after 15000 waves for the large-scale test (L1) and the small-scale test (3D-1). The comparison is very good; the position and magnitude of the beach crest is similar and also the position and magnitude of the maximum erosion is similar. The main difference is that in the large-scale test accretion occurs around the water level while in the small-scale test the waterline is nearly constant. Below the waterline there is a section with some erosion in the small-scale test while the large-scale test shows some accretion.

5. Conclusions

The response of gravel beaches under wave attack and the response of revetments with small rock such as cobbles have been studied. By performing laboratory investigations in a wave flume for small-scale tests, a wave flume for large-scale tests at a close-to-prototype scale, and a wave basin for 3D tests, some fundamental aspects have been studied. The large-scale tests can be seen as scale tests for cobble beaches (*e.g.* 1:4 - 1:10) and as 1:1 tests for gravel beaches. In all tests an initial slope of 1:8 has been applied. The following conclusions have been drawn:

- A homogeneous mound of gravel/cobbles with an initial slope of 1:8 leads to a more dynamic response than a 1:8 revetment of gravel/cobbles with an impermeable subsoil. It is expected that for initial slopes steeper than 1:8 the homogeneous structure is not necessarily the most dynamic. The average slope in the region between the beach crest and the maximum erosion depth, is the steepest for the most permeable structure (*i.e.* the homogeneous structure).
- If the pores between gravel/cobbles are filled with sand, the response becomes less dynamic. This results in a lower beach crest and less erosion below water. The results from these model tests indicate that erosion rates of gravel beaches can be reduced by the presence of sand in the toplayer. Considering that the percentage of sand in the gravel/cobbles may vary during the lifetime of revetments, these variations in time may affect the response of the revetment.
- The response of a gravel/cobble beach where sand is added later to the gravel (thus with grain structure) is different from a beach where the gravel and sand are mixed (thus without grain structure); for the mixed beach the amount of accretion and amount of erosion are larger.
- From the comparison between small-scale tests and large-scale tests it can be concluded that small-scale tests provide valuable qualitative information for situations where the pores of gravel/cobbles are not filled with sand. The tests indicate that the results from small-scale model tests with dynamic slopes consisting of small material are affected by model and scale-effects and should therefore be interpreted carefully, especially if not all geometric parameters are scaled exactly.
- If the pores of the gravel/cobbles are filled with sand, the model and scale-effects are larger; above water (where accretion occurs) there are some similarities but below water (where erosion occurs) the differences are large.
- The 3D tests with perpendicular wave attack show that for the tested condition the average profile provides a good representation of the results; the differences between the individual profiles are small, although slightly larger than in the wave flume tests.
- The 3D tests with perpendicular wave attack show that a combination of short-crested waves with 20% of the energy in low-frequencies of the generated wave spectrum leads to considerable differences compared to a 3D test with long-crested waves without low-frequency energy in the generated wave energy spectrum.

It is recommended to take above-described findings into account for the design of sea defences that use gravel or small rock in the primary armour layer. For an application of a gravel/cobble beach in a man-made sea defence reference is made to Loman *et al* (2010).

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