GRAVEL BEACHES WITH SEAWALLS

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This paper focusses on some fundamental aspects of gravel beaches and revetments with dynamic rock slopes. Obviously, the response of gravel beaches depends on parameters such as the wave height and the stone size. Here, other parameters such as the permeability of the subsoil, the influence of sand in the pores of gravel, and the influence of seawalls have been studied. The results from the physical model tests indicate that a homogeneous mound of gravel with an initial slope of 1:8 leads to a more dynamic response than a gravel beach with an impermeable subsoil. The results also show that if the pores are filled with sand, the response becomes less dynamic. Placing a seawall on a gravel beach may be interesting for gravel beaches that serve as (man-made) sea defence. Furthermore, the results provide insight into the magnitude of scale effects.

Keywords: rock slopes; gravel beaches; cobble beaches; seawalls; dynamic revetments; wave flume; permeability.

INTRODUCTION

Natural gravel beaches exist (see Fig.1) but a gravel beach can also be used as part of a coastal defence system. 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. This paper focusses on aspects that are relevant for coastal revetments that consist of gravel or small rock.

Figure 1. Natural gravel beach.

The response of gravel beaches depends 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:

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1. How does the permeability of the subsoil affect the dynamic response of gravel beaches?
2. If the pores of the gravel are filled with sand, how does this affect the dynamic response?
3. Is the dynamic response of gravel of which the pores are filled with sand, after the gravel has been placed, significantly different from the response of beaches where sand and gravel are mixed before placement (thus without grain-structure)?
4. What is the influence of seawalls on the response of gravel beaches?
5. What is the magnitude of scale effects between laboratory investigations on the dynamic response of gravel and cobble beaches on a small scale and similar investigations on a large scale?

The purpose of a seawall on a gravel beach is to reduce wave overtopping. This can be required to lower the wave overtopping for sea defences that have been constructed too low (or for a too low return period), or to limit the required space for the sea defence compared to a longer slope that consists of gravel. However, the response of gravel will be different with a seawall in the active section of the gravel beach (due to wave reflection and due to the obstruction of the upward transport of gravel).

To provide insight into these aspects laboratory investigations are performed in two wave facilities of Deltares | Delft Hydraulics: a wave flume for small-scale tests and a wave flume for large-scale tests.

LABORATORY FACILITIES

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 tests waves up to H_s=1.35m were generated in the large-scale tests and waves up to H_s=0.24 m for the small-scale tests.

Figure 2. Small-scale (left) and large-scale (right) wave flume tests.

SMALL-SCALE WAVE FLUME TESTS

Test set-up

Small-scale tests were performed to provide insight into all research aspects mentioned in the introduction. Six test series (S1-S6) were performed for these purposes. Table 1 provides an overview of the test programme. 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 Fig.3), except for Series S5 and S6 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			
		impermeable	homogeneous	sand in pores			mixed
				0%	20%	max.	
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			
S6	Seawall		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). In Series S6 a seawall was placed at four different positions in the active part of the gravel beach, see lower graph in Fig.3. One seawall was placed at the waterline and three seawalls were place slightly more upward at locations where without seawall a beach crest was present.

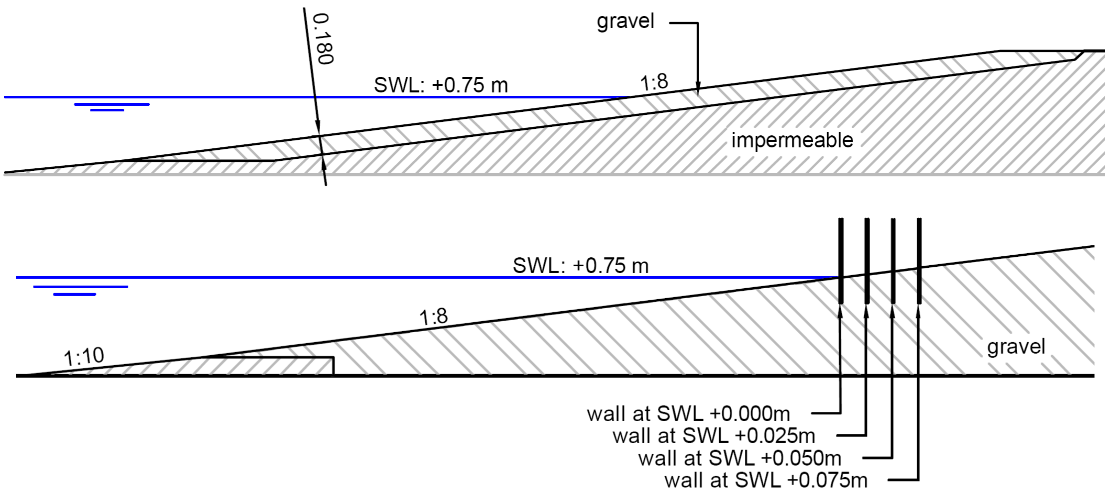

Figure 3. Model set-up in small-scale tests; upper graph for Series S1-S4, lower graph for Series S5-S6.

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 beach in time (without sand in pores)

Fig.4 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.

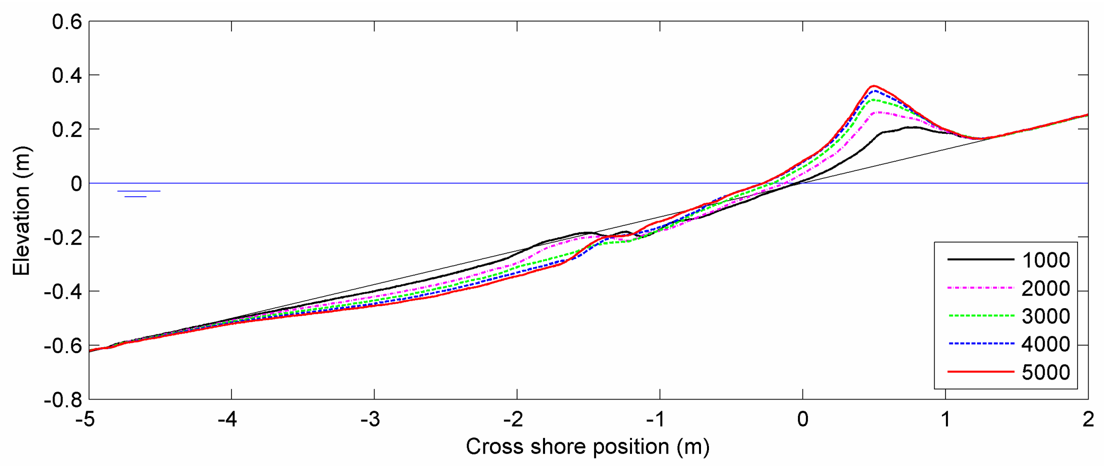

Figure 4. Small-scale tests: Development in time (no sand in pores).

To study whether the results can be reproduced Series S1 has been repeated. Fig.5 (profiles after 5000 waves) shows that the differences are rather small; the beach crests are nearly the same, some minor differences occur in the section with erosion.

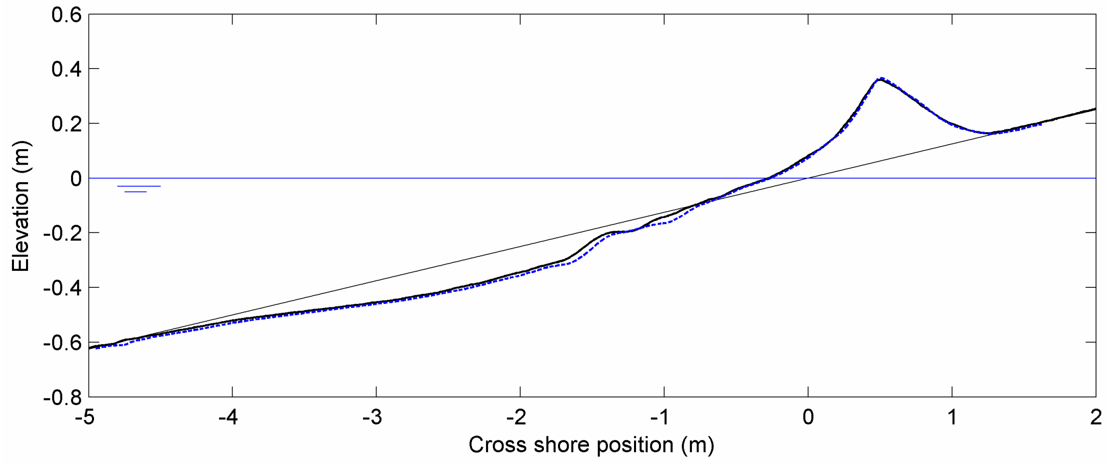

Figure 5. Small-scale tests: Repeatability of tests (no sand in pores).

Response of gravel beach with sand in pores

Fig.6 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.

Fig.7 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). Fig.7 (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.

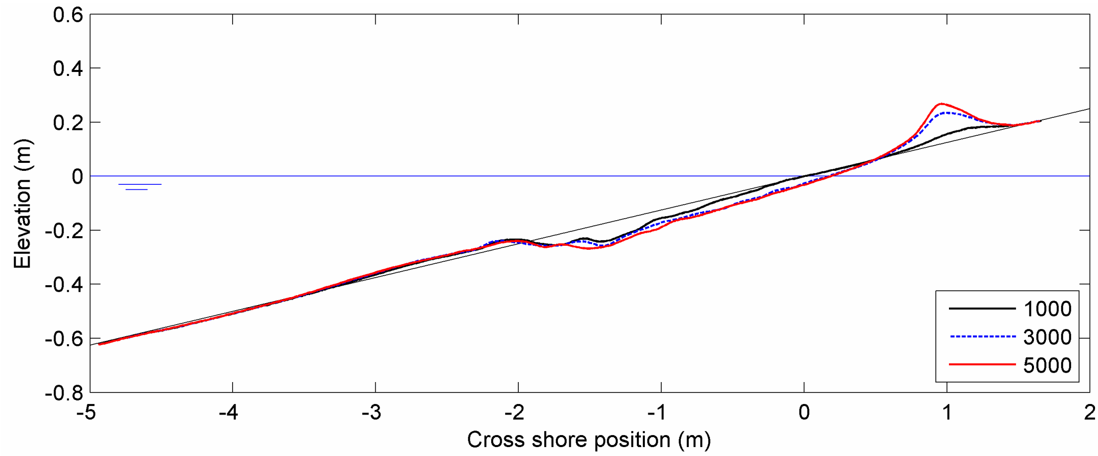

Figure 6. Small-scale tests: Development in time (with sand in pores).

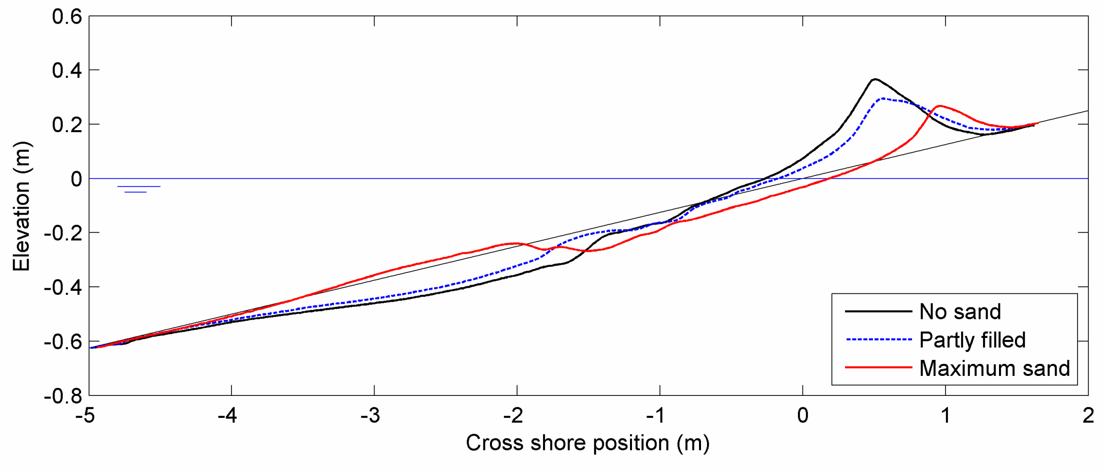

Figure 7. Small-scale tests: Comparison of profiles with and without sand in pores.

Influence of "grain structure"

Fig.8 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").

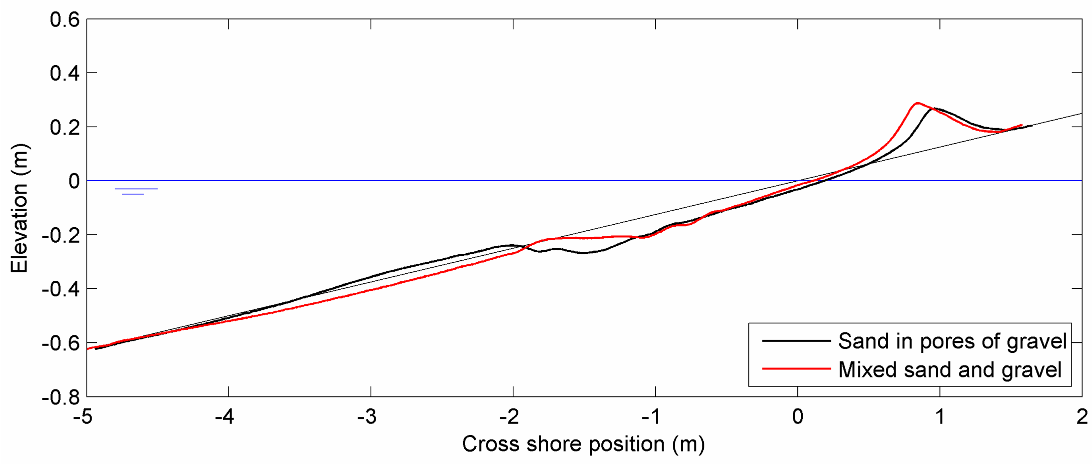

Figure 8. Small-scale tests: Comparison between profiles with sand in pores and a mixed beach.

Influence of permeability of the subsoil

Fig.9 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). Fig.9 (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).

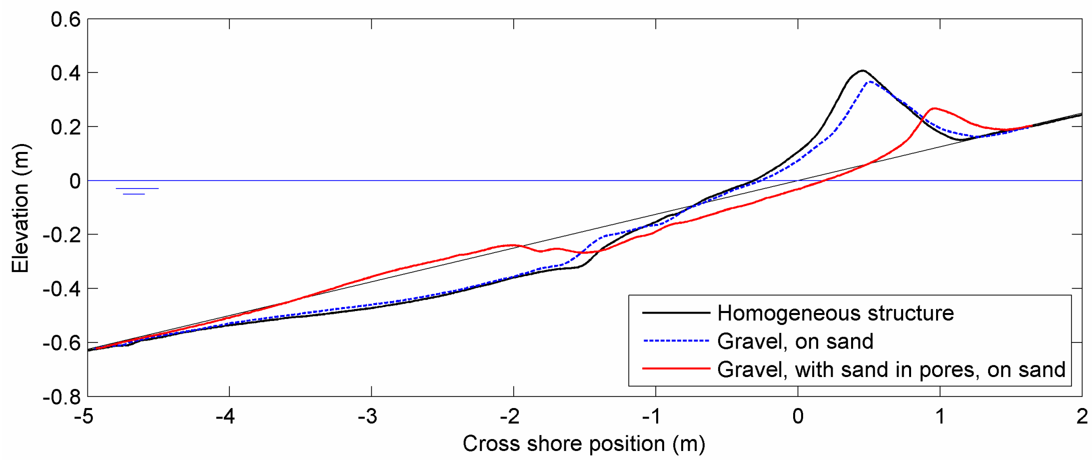

Figure 9. Small-scale tests: Influence of permeability (homogeneous, gravel on an impermeable core, and gravel with sand in pores on an impermeable core).

Influence of seawall on response of gravel beaches

Fig.10 shows the response of the gravel beach in time for Series S6, after approximately 1000, 2000, 3000 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 piling-up of material in front of the seawall. The results show that the slope of the gravel beach in front of the seawall becomes steeper in time, that the waterline moves seaward in time, and that the maximum level reached by the gravel in front of the seawall increases in time. No erosion occurs directly in front of the seawall.

Fig.11 shows the response of the gravel beach depending on the position of the seawall (after 5000 waves). This figure shows in all situations piling-up of material in front of the seawall. Especially seaward of the original waterline the profiles are very similar, except that the more the seawall is positioned seaward, the more seaward the beach is positioned.

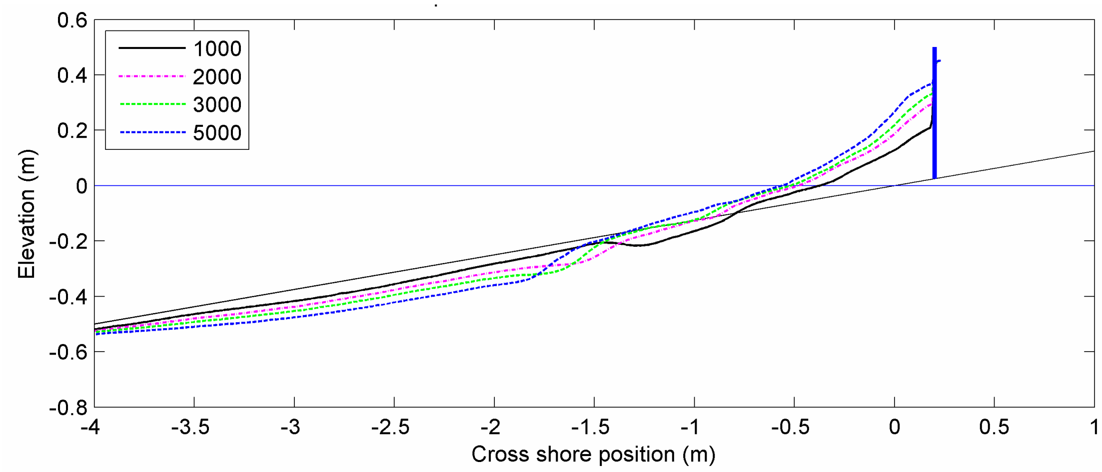

Figure 10. Small-scale tests: Development in time of gravel beach with seawall.

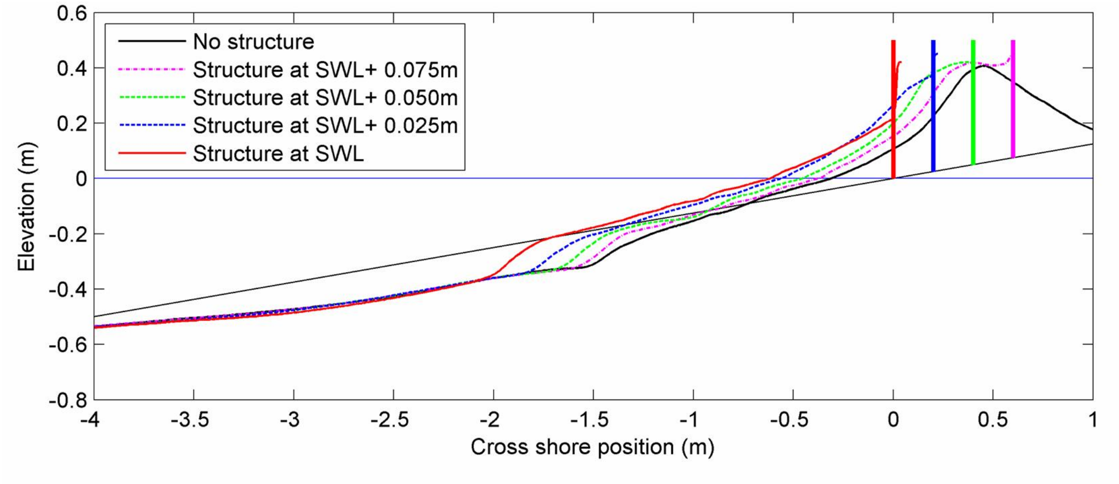

Figure 11. Small-scale tests: Influence of the position of the seawall.

LARGE-SCALE WAVE FLUME TESTS

Test set-up and test programme

Large-scale tests were performed to provide insight into the second, fourth and fifth aspects mentioned in the introduction: If the pores of the gravel are filled with sand, how does this affect the dynamic response, how does a seawall affect the response of the gravel beach, and what is the magnitude of scale effects? Three test series (L1, L2 and L3) were performed for these purposes. Series L1 was performed without sand in the pores of the gravel. Series L2 was performed with sand in the pores of the gravel. Series L3 was performed with a seawall on the gravel beach. 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 Fig.12). 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.

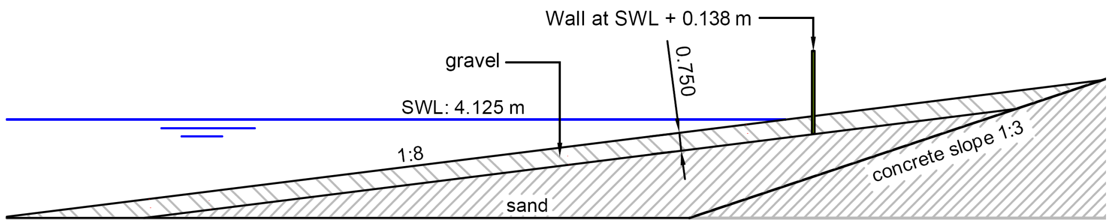

Figure 12. Model set-up in large-scale tests.

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 5 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.

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
L3	Seawall on gravel beach	X	X	

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). Series L3 was performed with a seawall placed on top of the sand layer.

Figure 13. Large-scale tests with gravel (after Series L1 and L3).

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. Fig.13 shows a few pictures of the gravel beach after Series L1 and L3.

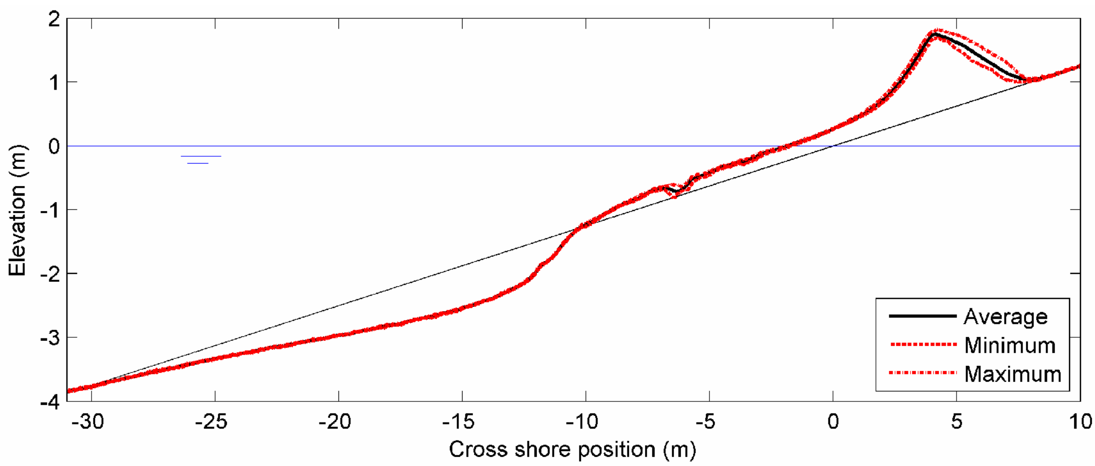

Figure 14. Large-scale tests: Differences between individually measured profiles and the average profile.

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. Fig.14 shows the average profile together with the largest differences of individual profiles (*i.e.* envelop); noticeable differences only occur at the rear side of the beach crest and in a section with a scour hole at a depth of approximately 0.5 H_s.

Response of gravel beach in time (without sand in pores)

Fig.15 shows the response of the beach in time. This figure shows that above the water level there is only accretion while the erosion takes place below water. The following observations were made:

- The height of the beach crest increases with an increasing number of waves (in this test up to about 1.3 H_s above the water level after 17000 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 dominated by the initial run-up; the distance of the 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 17000 waves this point is approximately 1 H_s below the water level.
- Below the water level there is a significant section with erosion; the depth where this erosion starts is rather constant (1 H_s) but with an increasing number of waves the section with erosion extends to deeper water. After about 17000 waves this section with erosion reaches a depth of about 3 H_s .
- These described trends were also observed in the small-scale tests, although the values are different; the height and position of beach crest, and the depth and position of erosion are different.

Response of gravel beach in time (with sand in pores)

Fig.16 shows the response of the beach profile for Series L2 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. Below water there is also a clear section with accretion. Erosion takes place at both sides of this section with accretion. Around the waterline there is no erosion or accretion.

Fig.17 shows the comparison of the tests with (maximum amount of sand) and without sand in the pores. Fig.17 (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 between large-scale and small-scale tests (without sand in pores)

Fig.18 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.

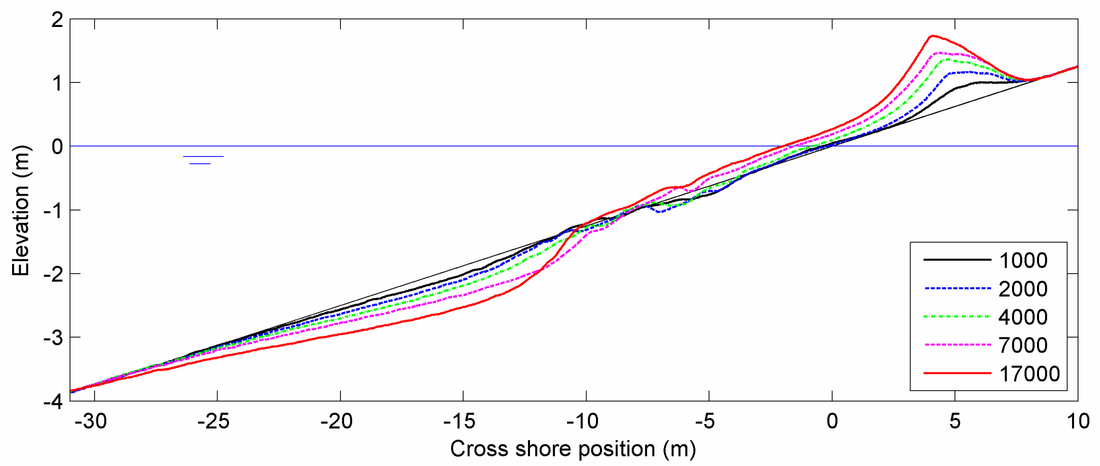

Figure 15. Large-scale tests: Development in time (no sand in pores).

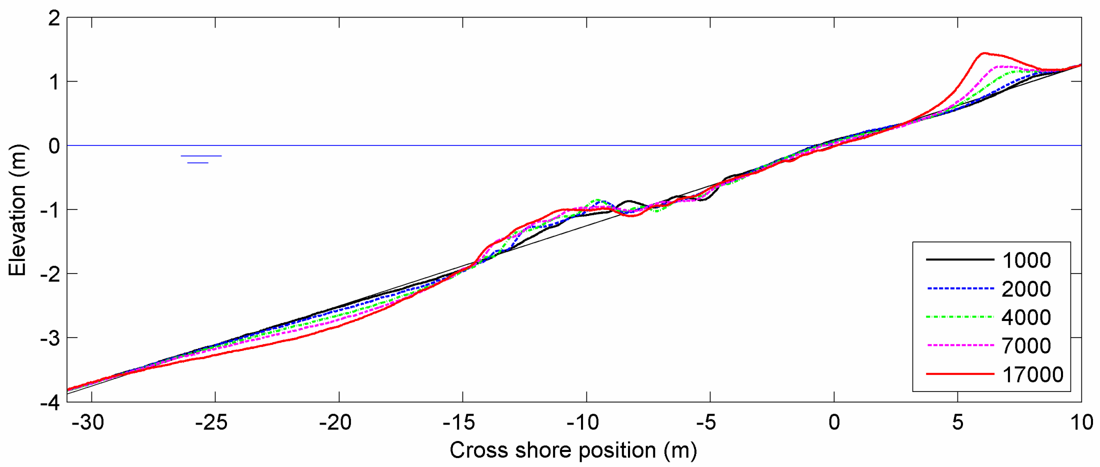

Figure 16. Large-scale tests: Development in time (with sand in pores).

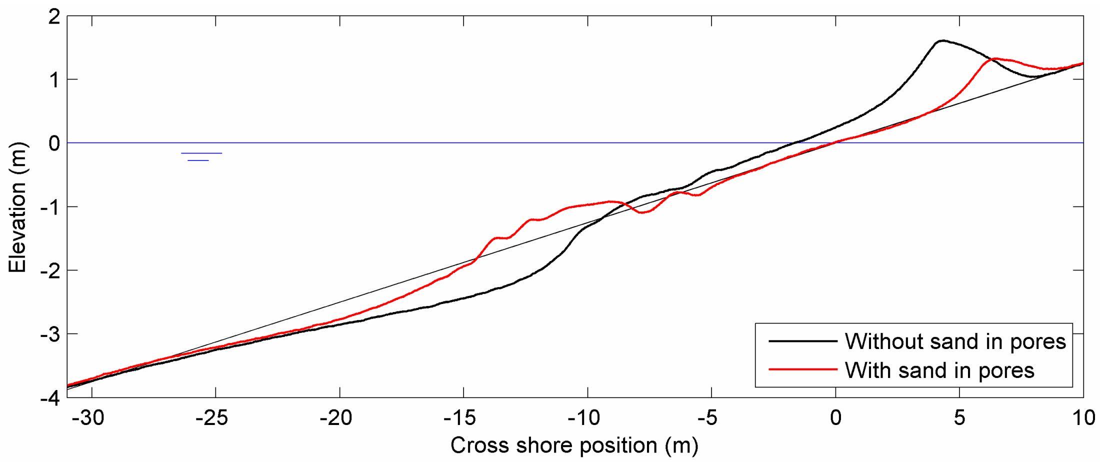

Figure 17. Large-scale tests: Comparison of profiles with and without sand in pores.

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. Fig.18 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 2 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 2 larger in the small-scale tests.
- The waterline moves seaward both in the large and the small-scale test; the differences are small.

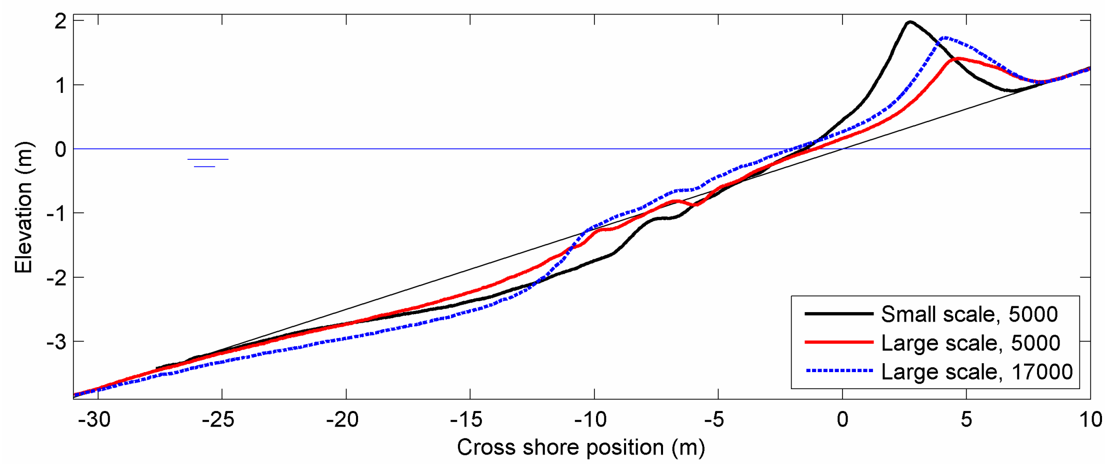

Figure 18. Comparison between large-scale and small-scale tests (no sand in pores).

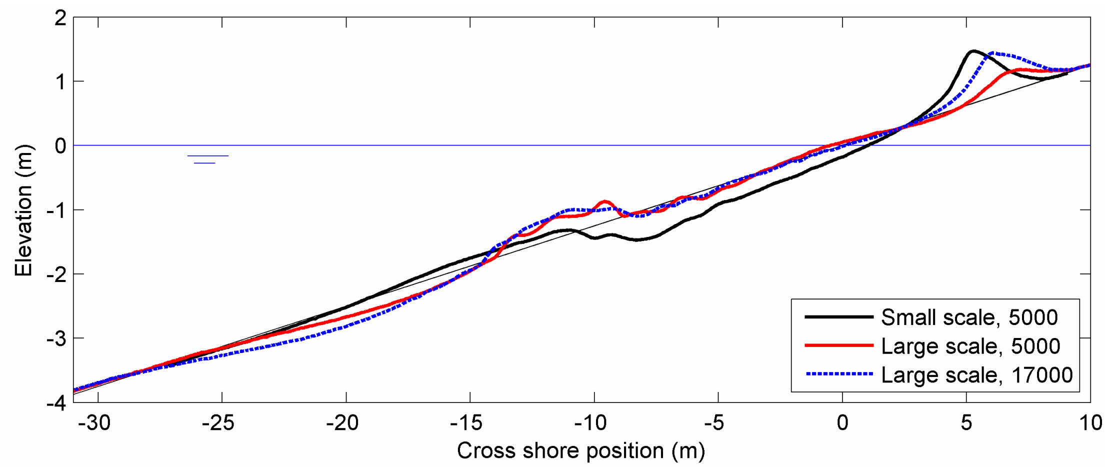

Figure 19. Comparison between large-scale and small-scale tests (with sand in pores).

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

Fig.19 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.

Response of gravel beach with seawall

Fig.20 shows the response of the gravel beach in time for Series T3, after approximately 1000, 3000, 5000, 7000 and 13000 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. The results show some differences from the small-scale tests shown in Fig.10 and Fig.11 (*e.g.* the maximum level of gravel in front of the seawall does not vary in time, see for the small-scale tests Fig.10) but also some similarities. Fig.20 shows again piling-up of material in front of the seawall. The large-scale test shows the formation of a bar and erosion on both sides of the bar, while the landward scour hole is filled up with gravel in time and becomes a region of accretion (see also Fig.10). Also here the waterline moves seaward in time and no erosion occurs directly in front of the seawall.

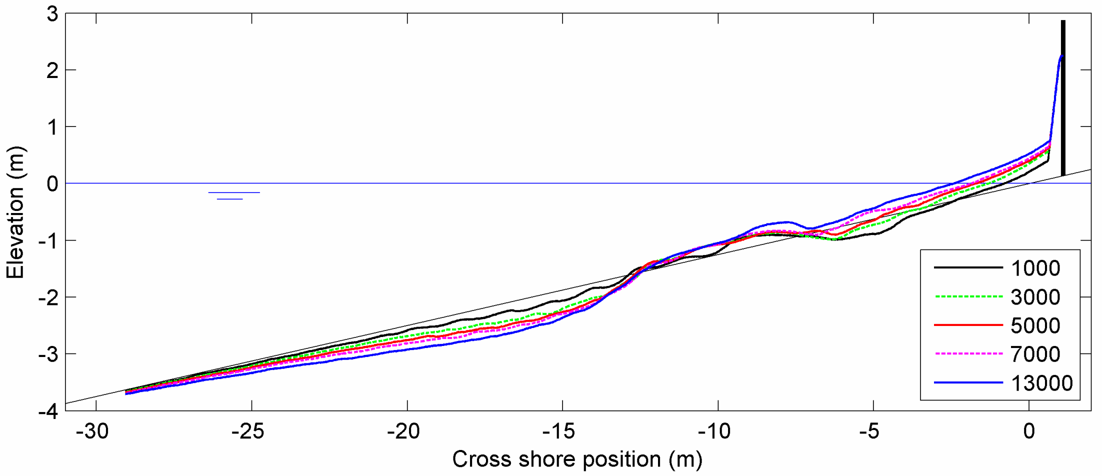

Figure 20. Large-scale tests: Development in time of gravel beach with seawall.

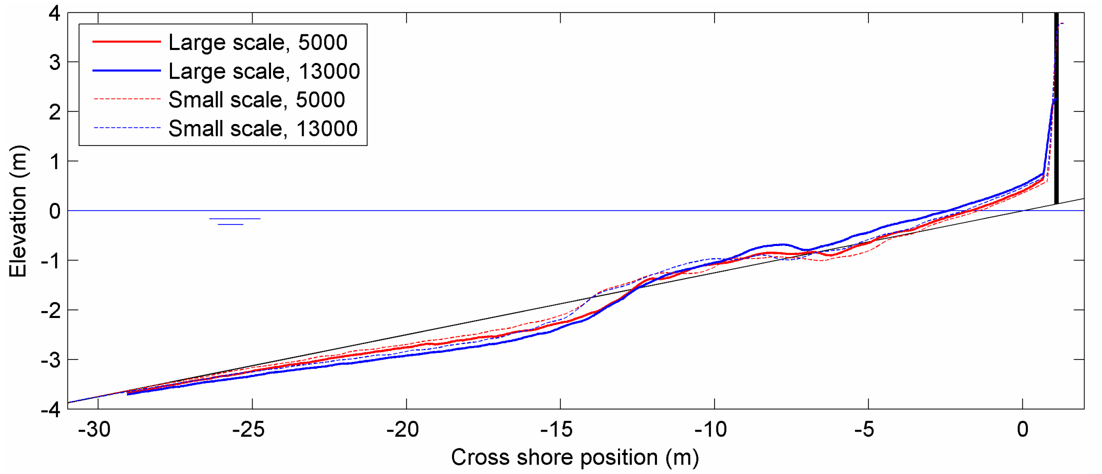

Figure 21. Comparison between large-scale and small-scale tests with seawall.

As mentioned before, there are a few differences between the small-scale model and the large-scale model, for instance the large-scale tests has a layer of sand (impermeable) underneath the gravel. To exclude potential sources of differences between the large-scale test and small-scale tests, the large-scale test has been repeated with a new small-scale test, now with the configuration of Fig.12 scaled 1:6.6. Thus, the new small-scale test was performed including the impermeable underlayer and gravel such that ΔD_{n50} is a factor 6.6 smaller.

Fig.21 shows the comparison between this small-scale test and the large-scale test. The results shows that piling-up of gravel in front of the seawall is very similar, that in both tests a bar is formed with erosion on both sides, and that the steepness of the gravel beach above the water level is very similar. After 5000 waves the amount of erosion and accretion is similar in both tests; especially landward of the bar the profiles are very similar. After 13000 waves the amount of erosion and accretion is somewhat larger in the large-scale tests. In the small-scale tests the bar is somewhat more seaward than in the large-scale tests. Nevertheless, the overall similarity between the small-scale test and the large-scale test is good.

CONCLUSIONS AND RECOMMENDATIONS

The response of gravel beaches under wave attack has been studied. By performing laboratory investigations in a wave flume for small-scale tests and a wave flume for large-scale tests at a close-to-prototype scale, some fundamental aspects have been studied. In all tests an initial slope of 1:8 has been applied. The following conclusions have been drawn:

- A homogeneous mound of gravel with an initial slope of 1:8 leads to a more dynamic response than a 1:8 revetment of gravel 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 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 may vary during the lifetime of revetments, these variations in time may affect the response of the revetment.
- The response of a gravel 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.
- Placing a seawall on the gravel beach can reduce the length of the gravel beach considerably, and may be interesting for gravel beaches that serve as (man-made) sea defence. The tests indicated that if the seawall is placed in a section where accretion takes place without the seawall, also accretion takes place with the seawall: No erosion takes place in front of the seawall.
- 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 are not filled with sand. These 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 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 comparison between the results from the large-scale test and the small-scale test with a seawall is good. The results indicate that for gravel beaches without sand the small-scale tests show good resemblance with large-scale tests if all geometric parameters are scaled properly.

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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