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Original Paper

LABORATORY INVESTIGATION ON GRAVEL AND MIXED BEACHES DURING AN OBLIQUE WAVE ATTACK

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ABSTRACT

An experimental investigation into the behavior of gravel and mixed (sand and gravel) beaches was carried out at the 3-D Wave Basin located at Franzius-Institute (Marienwerder) of University of Hannover, at a nominal scale of 1:1. The experiment aimed to provide full scale measurements of cross-shore processes on gravel and mixed beaches, during an oblique wave attack, with uniform slope and a trench. Measurements included sediment transport, cross-shore beach profiles and wave-induced currents, for regular and random wave tests, for both types of beaches. Analysis of both cross-shore and long-shore currents shown interesting behaviour for both gravel and mixed beach, especially at the trench. There were morphological differences between the two types of beach concerning the crest and the step formation, the onshore sediment movement, and the erosion below the SWL, concluding the general difference of their mobility.

INTRODUCTION

Due to global warming and climate change, there is increased storminess and sea level rise. As a result erosion of the world's coastlines has become a well-known phenomenon (Watt and Moses, 2005). A coastal protection with an economical solution is needed. Coastal managers and coastal engineers are beginning to give attention to gravel and mixed beaches due to the fact that both are two of the most effective natural sea defenses (Watt and Moses, 2005).

Over the past few years the majority of existing coastal research has been conducted on sand beaches (Watt and Moses, 2005). Comparatively little research has been carried out using gravel beaches, such as the laboratory studies of van der Meer and Pilarczyk (1986), Blewett et al. (2000), Pedrozo-Acuña et al. (2006) and the field surveys/observations of Allan and Komar (2002) and Austin and Masselink (2006). Even less research has been conducted on mixed beaches such as the laboratory studies of Pedrozo-Acuña et al. (2007) and Lopez de San Roman-Blanco et al. (2006),field observations of Kulkami et al. (2004), Pontee et al. (2004), Ivamy and Kench (2006) and Ciavola and Castiglione (2009). As a result, this research field is at its early stages. These beach types show important differences in their morphodynamic responses to environmental conditions despite the fact that there are general principles that can be applied to them. The different sediment sizes within mixed beaches, makes them more complex than the gravel beaches.

Gravel beaches are an important landform, and due to their distinct properties, they have a number of applications for sea defence and coastal protection. With continued research, gravel beaches should become more widely recognized for the role they play as a highly effective and dynamic buffer against the forces of the sea. Gravel beaches are highly efficient dissipators of wave action and they can provide excellent natural or managed defence systems. They are particularly efficient, since their high permeability enables energy loss through percolation within the beach (Watt and Moses, 2005).

There are several existing models derived for gravel beaches such Powell's (1990) parametric modelling approach (SBEACH), the numerical model BeachWin used by Li et al.

(2002) and Horn and Li (2006), the process-based approach of Pedrozo-Acuña (2005) and the numerical model of Pedrozo-Acuña et al. (2006).

Most of the numerical models have been derived for sand beaches and extrapolated for use on coarse-grained beaches, such as a the numerical model XBeach which was originally developed for sandy environments (Roelvink et al., 2009) and modified for use in predicting the cross-shore profile changes of gravel beaches (Jamal, 2011). The main problems encountered in this method are set out in Coates and Mason (1998) and Blanco et al. (2000).

There are some models derived for mixed beaches such as Powell's (1993) modified SHINGLE model with the option of dissimilar sediment model, the model of Wilcok and Kenworthy (2002), the conceptual model of Pontee et al. (2004), the numerical model of Lawrence and Chadwick (2005), LITPACK sediment transport model of DHI Software and the model of Jamal et al. (2010). However, none of them were able to fully estimate the morphological behavior of mixed beaches. The processes that control mixed beach morphology are still poorly understood.

The energy dissipation in mixed beaches depends on the proportion of sand compared to gravel (Antoniadis, 2009). Because of the limited understanding surrounding these beaches, mixed (sand and gravel) coastlines have a lot of research potential for both coastal resource management and scientific reasons. Despite the fact that these beaches are rarely found on a world-wide scale, mixed sediment beaches occur commonly around the shores of regions where the effects of glaciation have provided an abundant source of sand and gravels for subsequent re-working by Holocene rising sea levels (Mason & Coates, 2001), including the UK, Eire, Canada and the Arctic Sea coast (Carter et al., 1990a; Finkelstein, 1982; Hill, 1990), Tierra del Fuego (Bujalesky and Gonzalez-Bonorino, 1991), New Zealand (e.g. Kirk, 1969) and Greece (Moutzouris, 1991).

However these beaches in common with the other types of beach will suffer erosion under extreme conditions of storm events with high water level. Therefore, predicting their evolution is a critical issue due to the fact that pattern of accumulation or erosion can be identified and calculated. Thus, an accurate assessment and maintenance of the beach structure can be done and the beach failure can be prevented. Therefore, there is a need, from a scientific and coastal management perspective to have a deeper understanding of how gravel and mixed beaches operate.

The importance of laboratory experiment is well known for scientific research, since experiments give rise to the opportunity to check on the accuracy of theoretical models, and also improve on the understanding of the physical processes involved in the theoretical model (Hughes, 1993). The laboratory experiments have the advantage of creating controlled conditions. With the help of highly sensitive equipments, laboratory experiments can facilitate accurate measurements and reduce significantly the cost in comparison to the field studies. Despite that, laboratory experiment is not a field experiment, meaning that it cannot replicate exactly the real natural conditions. Because of that, extensive care is taken when constructing the basin geometry and the boundaries, so that the designed wave-current system is not significantly affected by scaling.

An important contribution in understanding the gravel and mixed beaches dynamics was the work of Lopez de San Roman-Blanco et al. (2006) with the large scale experiments which were undertaken at the Large Wave Channel (GWK) of FZK in Hannover. Lopez de San Roman-Blanco et al. (2006) investigated the behavior of the gravel and mixed beaches during normal wave attack and has developed a conceptual model of gravel and mixed beach processes.

In the present study, the experiments at the 3-D Wave Basin located at Franzius-Institute of University of Hannover were undertaken with the main objective to gain detailed knowledge on the produced wave-induced currents and on their impact on the cross-shore sediment transport along a uniform slope and a trench for both types of beaches (gravel and mixed). Previous published results related to gravel and mixed beaches, performed in large wave tank under oblique wave attacks do not exist. In particular, studies on mixed beaches are rare (Jamal, 2011).

Comparative results between the gravel and mixed beaches help to understand their differences and similarities and what will be the influence of a feature (trench) in their behavior.

The design of civil engineering projects, such as pipelines, often requires the dredging of trenches. In order to estimate the fluid forces acting on the submerged structure or to compute the siltation rate of the dredging trench, detailed knowledge on the patterns of the produced flow field is of particular importance. A trench could be used as a coastal defense feature, when the along-shore sediment transport rate of the beach is rather high. The trench acts as a sediment trap, where bed load and suspended sediments settle into it as a result of the alongshore sediment transport process. Detailed knowledge and quantification of this sediment transport could be of particular importance for trench design as a coastal protection system. Therefore, it appears important to include the trench into the studied beach model and to investigate its hydrodynamic and morphodynamic behavior.

The data derived from the experiments will be useful to many researchers interested in beach response modelling. More detailed information about the experiments and the data can be found in Antoniadis (2009).

Materials and Methods

The experiments were carried out in the three-dimensional wave basin located at Franzius-Institute (Marienwerder), Hannover University. The experiments ran for nearly 70 days and were undertaken for a beach model which consisted at first of gravel sediment and secondly of mixed sediment.

The Wave Basin

The wave basin was sufficiently dimensioned for three-dimensional swell investigations. The wave basin had a length of 40m, width of 24m and could be filled up, to the maximum depth of water of 0.7m. The plant was controlled by separated mobile individual components, with a total width of about 25m. The stroke was of 0.7m giving better efficiency of the absorption control. The wave machine plates implemented a pure translation movement (piston type) and could be used in water depths of 0.7m. The plates were moved by oil hydraulic cylinders. Each of the machines was supplied with the intended capacity range by a pressure station. The overall system allowed the regulation units to control the valves of the hydraulic cylinders, and a computer was used for data acquisition and evaluation. A system was present for absorption control where the reflected waves were absorbed at the wave machine. At the other end of the wave basin were placed around 6 tonnes of gravel, in order to absorb the wave energy and diminish the reflected waves. Further details can be found in Zimmermann C. et al. (2000).

The Beach Model

The beach model with dimensions of 8m x 7m x 0.7m was set up in the middle of the wave basin. It was open to the side from which the generated waves were approaching. The beach model was oriented in such a way that waves, generated by the wave paddle, were always approaching it with an angle of 15^0 (

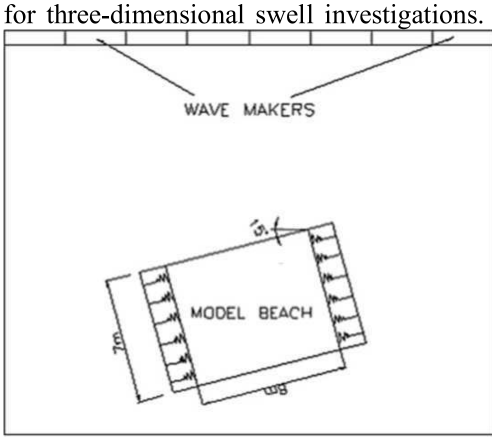

Figure 1). Beach bathymetry consisted of a uniform slope beach (straight-line parallel contour) and a trench (curved contour) with a width of 2m, as shown in Figure 2. The location and the dimensions of the trench in the physical model would not have any significant impact in the profile changes of the beach with the uniform slope.

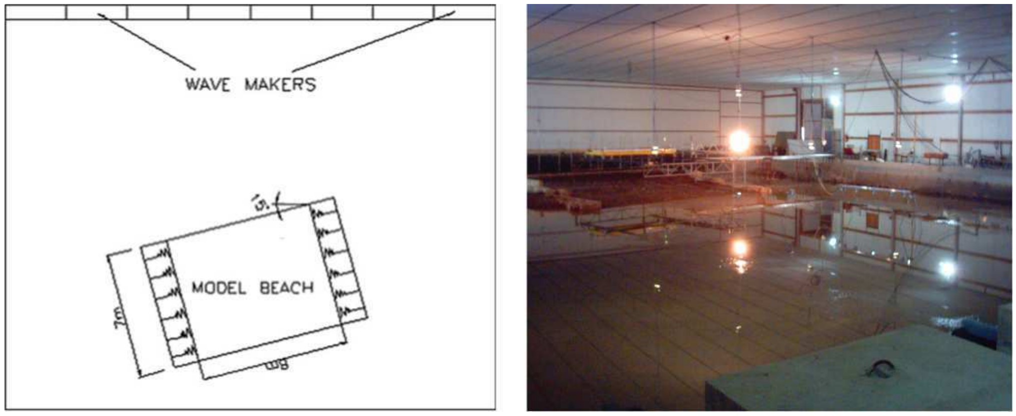

Figure 1. Orientation of the beach model

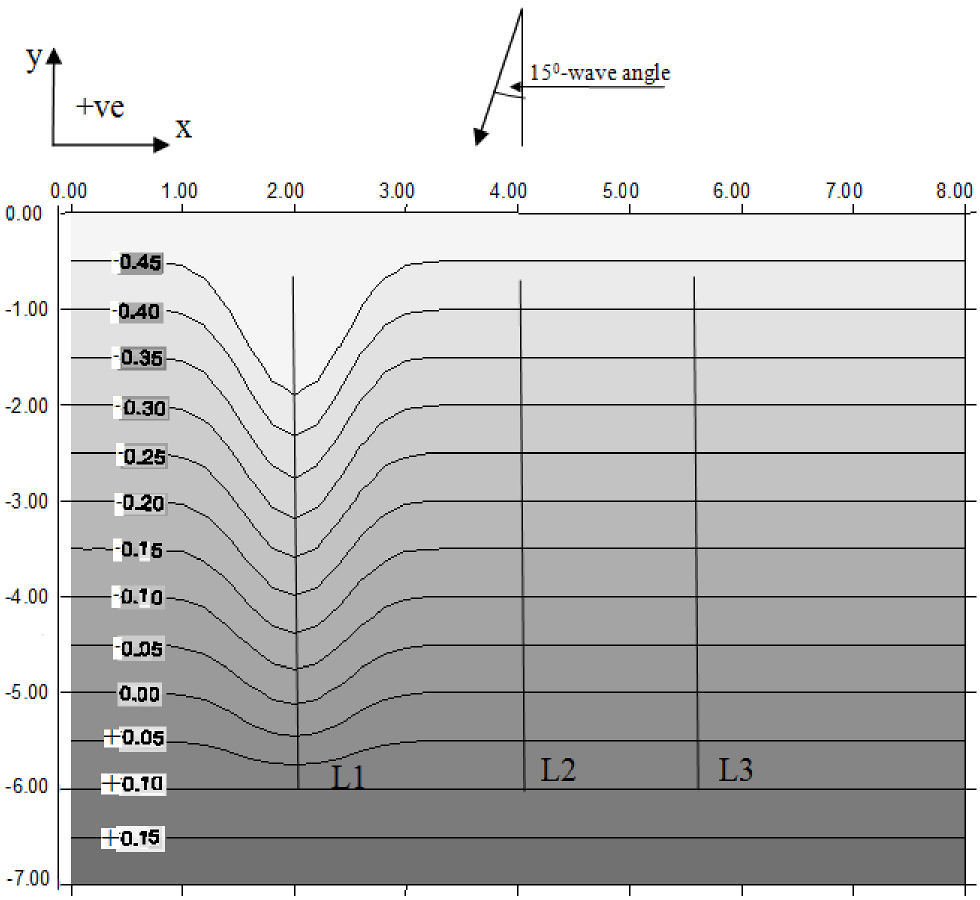

Figure 2. Bathymetry of the beach model (units in meters)

Sediment

The beach model was constructed twice for the purpose of the experiments. Both times different type of material was used. The two different beach set-ups were:

1. *Gravel beach* : this consisted of material sieved between 16 and 32mm, with a median diameter of $D_{50gravel}$ =22.76mm (Table 1). Although the gravel was not as perfectly rounded as that found on natural beaches, it was considered to be

within acceptable limits of angularity. The beach material porosity was around 0.45 and the density of the sediment was 2,450kg/m^3.

2. *Mixed beach*: this consisted of a bimodal mix between gravel and sand, which had a D_{50sand} =300μm. The median diameter of the mixed sediment was D_{50mix} = 12mm (Table 1). The percentage of sand in the mixture was around 40%. The sediment was thoroughly mixed prior to beach construction outside the wave basin and during beach construction within the wave basin. For the mixed beach, the porosity was far lower than that of the gravel beach, approximately 0.2 and the density of the sediment was 2,580kg/m^3.

Table 1 shows the initial sediment size distribution for both beach materials. Initially, the beaches were constructed at a 1:10 slope but they were not reshaped during the experimental procedure (except when the sediment changed), so that the initial condition for each test was the final profile from the previous test. Reshaping the beach in such a large facility would have been very time consuming and therefore not practical, and there are also uncertainties as to what should be an appropriate initial condition in any event. The beaches were conducted at this slope due to the fact that firstly, the gravel beaches are steep, in general steeper than about 1:10 and secondly, the mixed beaches can be steep reflective beaches which have in general a beach slope in the range of 1:10.

Table 1. The initial particle sizes of the sediments

Type of Beach	D_5 (mm)	D_{15} (mm)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{85} (mm)	D_{90} (mm)	D_{94} (mm)
Gravel Beach	15.35	16.66	16.83	22.76	28.38	28.86	29.59	30.50
Mixed Beach	0.21	0.32	0.33	12	25.20	25.9	27.31	29.19

Beach Construction

Two factors had to be considered for the construction of the beach model. These factors are discussed below:

- Compaction: in order to prevent different compaction of the sediments along the beach due to the machinery, resulting irregularities across the beach during the experiment, the sediments were compacted manually.
- Settlement: mixed beach appeared to be quite compacted at the end of the construction. However the basin was filled with water over 8 hours before carrying out the instrument calibrations. During this time, it was apparent that some settlement had taken place especially at the rear (at y=-7m) of the beach.

Instrumentation/Calibration

During the experiment, measurements were recorded concerning the water surface elevation further to the beach model, the water flow distribution at the surf and swash zone, and the beach profile changes at different locations. For these measurements, an Acoustic Doppler Velocimeter (ADV) and six wave gauges (GHM Wave Height Meter) were used. Wave gauges were placed offshore the beach model, where they measured water surface elevation, and consequently, the wave height and the wave period (Figure 3). The ADV was used to measure the wave driven current velocities and the beach profile changes.

The wave-height meter has been designed for dynamic fluid level measurements, e.g. wave-height measurements in hydraulic models. The instrument that was used in the experiment was composed of two parts: a gauge with integral pre-amplifier and a separate main-amplifier.

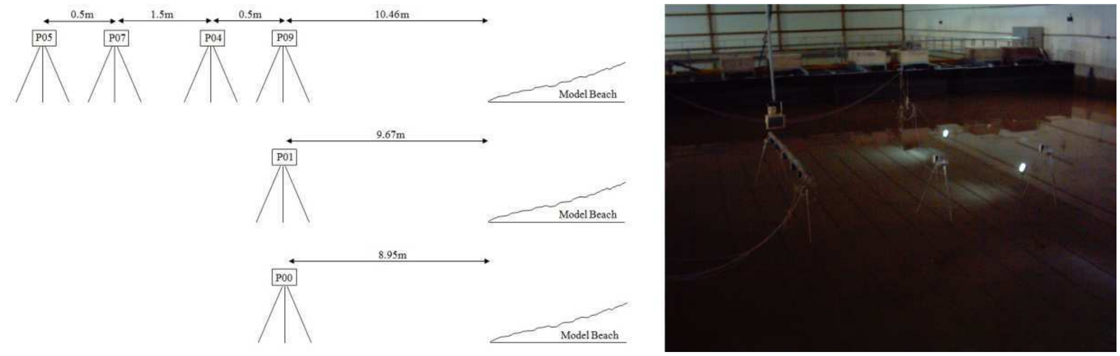

Figure 3. Location of the six wave gauges

Before the measurements started, the probe was attached to a point-gauge for calibration and fixed position for measurements. After calibration, the gauge was placed at the measuring-point ensuring that the wave crest met both rods simultaneously. There was no objection to execute/perform the calibration on the measuring-point, provided the water level remained sufficiently constant. When several wave gauges are placed close to each other, a certain mutual influence can be experienced, but as distances in that experiment were more than 20cm, this influence was neglected.

Finally the procedure for wave spectrum calibration was split into two parts, the first to record the spectral properties and to obtain the appropriate gain setting on the wave maker machine, and secondly to record the statistical properties of the spectrum over at least 1,000 generated waves. During testing, a similar procedure was used, usually, only statistical data was likely to be recorded. For both cases there was a consistency in recording.

Methodology

As the construction of the beach model finished, the experimental tests began. The experiment comprised of ten tests, which were mainly focused on the profile and wave current measurements across the gravel and mixed beach. However, the experiment involved making measurements of wave height and wave period. These measurements were carried out with the six wave gauges at the same locations, as the wave driven current measurements using an ADV. One of the six wave gauges was used as the representative gauge, the values from which were used for the test analysis. The observations started 10 minutes after the first wave was generated. These 10 minutes were sufficient to eliminate long-periodic start-related variations in wave fields.

The measurements of currents started 30 minutes after the first wave was generated for both regular and random waves. These 30 minutes were sufficient to eliminate bed level changes during the measurements, which could influence the currents. At that point, an equilibrium state was reached, in which no sediments were moving. However, for the mixed beach, the sand was moved slightly after the 30 minutes period, without any sufficient influence in the measurements. The currents were measured, in time, at three cross-shore sections of the beach. The first was at the curved beach section and the other two at the straight beach section, for all three space directions Vx, V_y and V_z. These sections are shown as lines in Figure 2. Velocities Vx and V_y were considered positive when heading towards the positive direction of x and y axes (

Figure 2), while the vertical velocity V_z was considered positive when heading upwards.

As far as the current velocities were concerned, the measurements had reached the maximum of -4.7m at y-direction due to the fact that the ADV can work only at submerged sections. Despite that, the number of current velocity measurements that was taken was satisfactory.

Current velocity measurements were carried out at various levels along the z direction. At each level, the current velocity measurements were taken over a period of 60 seconds. Observations for regular waves started at the surface and deepened with a constant 5cm integral until the maximum point was reached. The maximum point was the point at which the ADV could take logical measurements, usually that was between 5 and 10cm above the bed level. The deepest point of measurement was 35cm below water surface.

The same procedure was followed for random waves but with a 10cm integral. The deepest point of measurement for random waves was 30cm below the water surface. This procedure allowed an estimate of the vertical structure of the time-averaged velocity and a more accurate determination of the depth-averaged current velocities. The depth-averaged current velocity V was determined as:

Eq. 1

$$V = \frac{(V_{surface} + 2V_{mid-depth} + V_{bottom})}{4}$$

The ADV can measure the distance between the measured point, under the water, and the beach bed. Therefore, by placing ADV at the still water level, it can be used to measure the profile development of the beach at various locations. Due to the fact that ADV can only take measurements below the water level, its measurements were related to the submerged part of the beach. For the remaining part of the beach, the profile measurements were carried out with the use of a measuring stick. Measurements had taken place at 3 stages:

1. Before the generation of the waves (original profile).
2. At the end of the generation of waves for the initial test (the test with input wave period of 2 sec) and
3. At the end of the generation of waves for the second test (the test with input wave period of 3 sec).

The beach was reconstructed every time at its original shape after the completion of measurements at stage 3. Consequently, the beach was reconstructed five times in its original shape for both regular and random wave conditions

The profile and wave driven current measurements were taken at the three lines. The first was at Line 1 and the other two at Lines 2 and 3, respectively. These lines had a length of approximately 5.4m and their location can be seen in

Figure 2.

Test programme

Taking into consideration the maximum depth of water that the wave basin could be filled up and the height of the beach model, the value of Still Water Level (SWL) used for all tests was decided to be kept constant at 0.5m (maximum water depth). The test program of the experiment (for gravel (G) and mixed (M) beach) is listed in Table 2. These are the values that were measured by the representative gauge.

Table 2. Test program of the experiment

TESTS (Regular Waves)	Wave Height (H)	Wave Period (T)	TESTS (Random Waves)	Significant Wave Height (H_{m0})	Spectral Peak Period (T_p)
Test 1-G	0.253 m	2 sec	Test 5-G	0.108 m	2.3 sec
Test 2-G	0.218 m	3 sec	Test 6-G	0.11 m	3.2 sec
Test 3-G	0.086 m	2 sec	Test 9-M	0.11 m	2.3 sec
Test 4-G	0.092 m	3 sec	Test 10-M	0.117 m	3.1 sec
Test 7-M	0.086 m	2 sec			
Test 8-M	0.077 m	3 sec			

The values of the wave height and the significant wave height that were used, were chosen such that the same wave energy would be produced in test with both regular and random waves. The number of waves and their duration in each test is shown in

Table 3. With respect to the random waves, the wave paddles generated sequenced batches (C) with same wave spectra (JOHSWAP type), where each batch contained 116 waves.

Table 3. The time duration and the number of waves generated for each test

	Number of waves	Time Duration
Test 1-G	33,600	18h 40m
Test 2-G	18,250	15h 13m
Test 3-G	14,400	8h 00m
Test 4-G	7,450	6h 13m
Test 5-G	18,328 (C=158)	10h 32m
Test 6-G	12,412 (C=107)	10h 42m
Test 7-M	12,000	6h 40m
Test 8-M	7,900	6h 35m
Test 9-M	17,748 (C=153)	10h 12m
Test 10-M	12,644 (C=109)	10h 54m

Results and Discussion

Results for both regular and random waves were divided into four categories:
1. Wave parameters
2. Wave-induced current velocities
3. Cross-shore beach profiles
4. Sediment Balance

Wave Parameters

Based on the measured values and the angle at which the waves approached the beach (15^0), a series of wave parameters could be calculated. These are: deep water wavelength (L_0), wavelength (L), relative deep water depth (d/L_0), relative water depth (d/L), and wave steepness (H/L). The summary of all these wave parameters can be found in Table 4 below.

Table 4. Summary of calculated wave parameters

	H (m)	T (sec)	L_o (m)	d/L_o	d/L	L (m)	H/L
Test 1-G	0.253	2	6.245	0.080	0.123	4.056	0.062
Test 2-G	0.218	3	14.052	0.036	0.078	6.396	0.034
Test 3-G	0.086	2	6.245	0.080	0.123	4.056	0.021
Test 4-G	0.092	3	14.052	0.036	0.078	6.396	0.014
Test 5-G	0.108	2.3	8.259	0.061	0.105	4.770	0.023
Test 6-G	0.110	3.2	15.988	0.031	0.073	6.854	0.016
Test 7-M	0.086	2	6.245	0.080	0.123	4.056	0.021
Test 8-M	0.077	3	14.052	0.036	0.078	6.396	0.012
Test 9-M	0.110	2.3	8.259	0.061	0.105	4.770	0.023
Test 10-M	0.117	3.1	15.004	0.033	0.075	6.625	0.018

Examining the relative water depth (d/L), the values which were between 0.04 and 0.5 showed that the waves were in transitional water depth, whereas by examining the wave steepness (H/L), the values were smaller than 0.142 ($\frac{1}{7}$) which means that no wave broke before reaching the beach.

Wave-Induced Currents

The results for wave-induced current velocity measurements were divided into three categories: *time- and depth-averaged along-shore current velocities*, *time- and depth-averaged cross-shore current velocities* and *cross-shore current velocities near bed*.

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The graphical presentation of the results of the wave-induced current velocities at all directions for all the tests and for all the three lines can be seen in Antoniadis (2009). Examples of the results for the along-shore and the cross-shore current velocities, for both types of beach with random wave attack, are showed in Figure 4 and

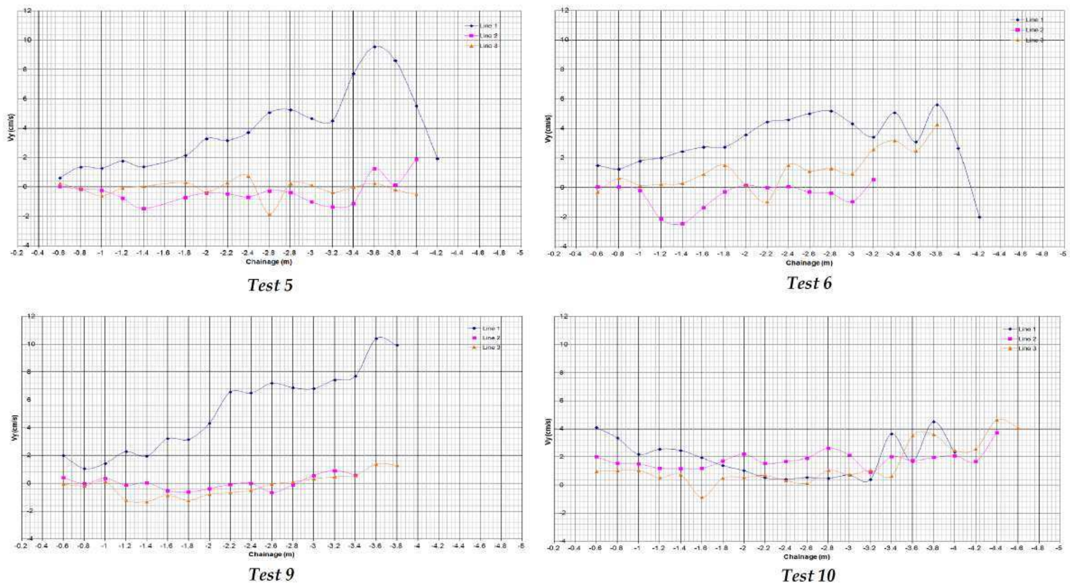

Figure 5, respectively. Each point of Vx and Vy represents the time- and depth-averaged current velocity of the location. It is worth noting that the negative values of the along-shore current velocities indicate the direction of the incoming waves and the negative values of the cross-shore current velocities indicate the shoreward direction.

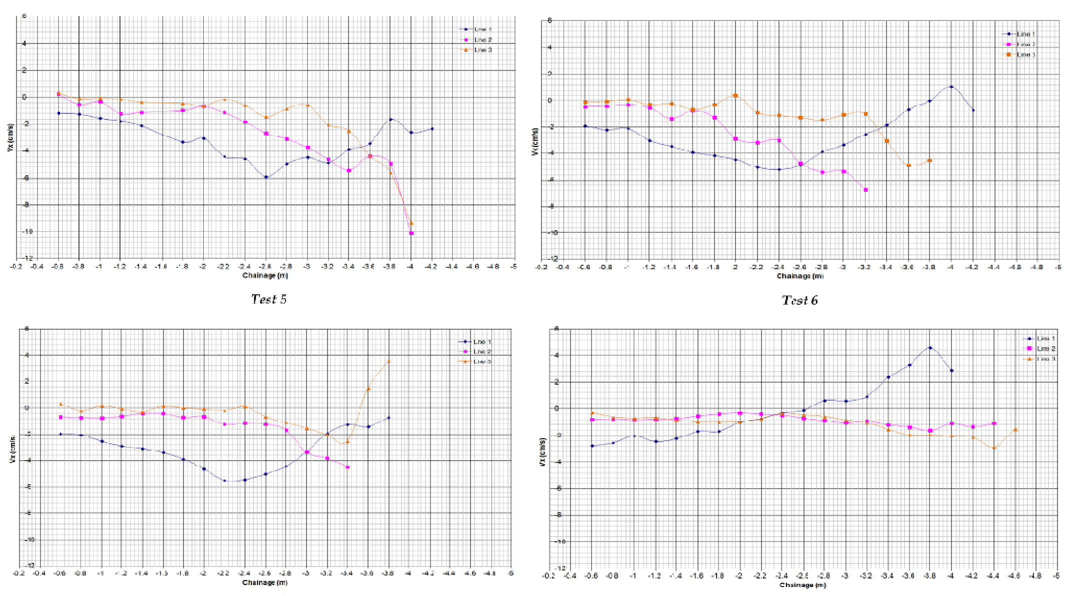

Figure 4. Wave-induced current velocity at x-direction

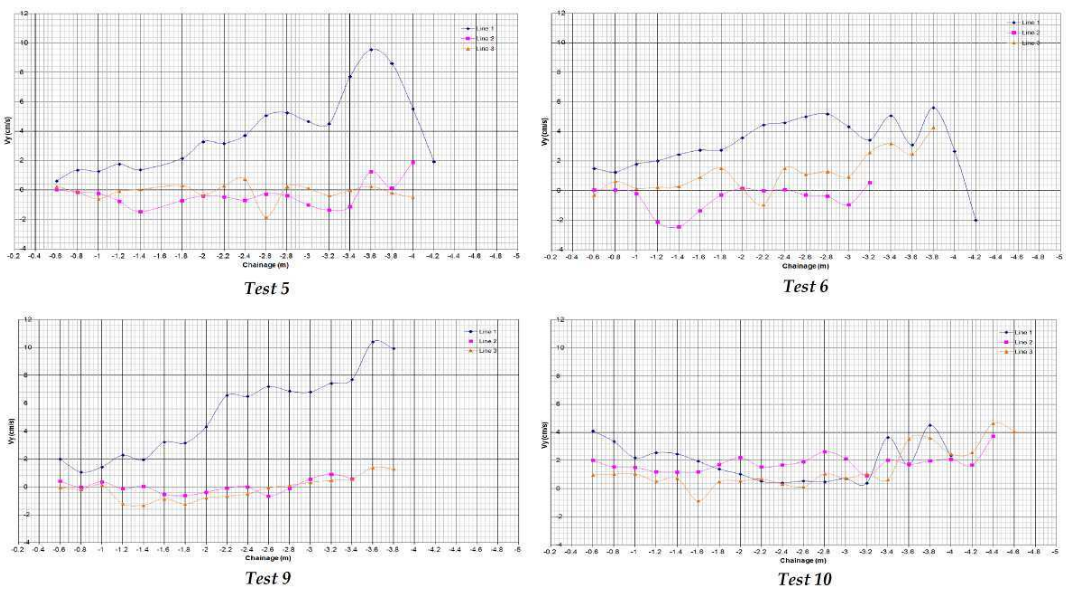

Figure 5. Wave-induced current velocity at y-direction

The along-shore current velocity of each line followed a similar pattern when comparisons were made between the same wave conditions for both types of beach. However, there was a forward shift of this pattern from gravel to mixed beach. This shift varied from 0.4 to 0.8m, with its maximum value being at trench. Initially, the along-shore current velocity at the trench was the smallest of the three lines due to the beach slope at that location.

The along-shore current velocity at the uniform slope followed the same pattern for both lines. Their along-shore current velocities had small values along most of the beach. However, after the wave breaking point, their values increased initially, at negative direction, until they reached their maximum values and then started to decrease as the end of the submerged beach was reached. Line 3 had higher values than Line 2 during all the tests for both types of beach. Therefore, the along-shore current velocities, at the beginning of the beach, had an opposite direction from the incoming waves indicating the existence of a reverse along-shore flow. Nevertheless, at trench the along-shore current velocities were not very small, except for some points at random wave conditions.

In all tests and lines, the cross-shore current velocity was inverse proportional to the along-shore current velocity. In contrast with along-shore current velocity, cross-shore current velocity was different for both gravel and mixed beach at the trench. However, Line 2 and 3 followed the same pattern (with a small shift between them) for all the tests, with Line 2 having often higher values than Line 3 (except at Test 5 and 6). Line 1 had, in general, the highest values of cross-shore current velocity. Frequently all lines had positive values of V_y. This pointed to an existence of a cross-shore flow with an offshore direction (reverse cross-shore flow). The behavior of cross-shore current velocity is different for both gravel and mixed beaches at the trench. However, it can be observed that at both gravel and mixed beach (for Tests 5 and 9) the V_y followed the same pattern at the trench. This was not the case for the other tests. Under the same wave conditions, whenever V_y for gravel started to increase (Test 6), the V_y for mixed beach became constant or even decreased (Test 10). Examples of the results of cross-shore current velocities near the bed, for both types of beach with random wave attack, are showed in Figure 6.

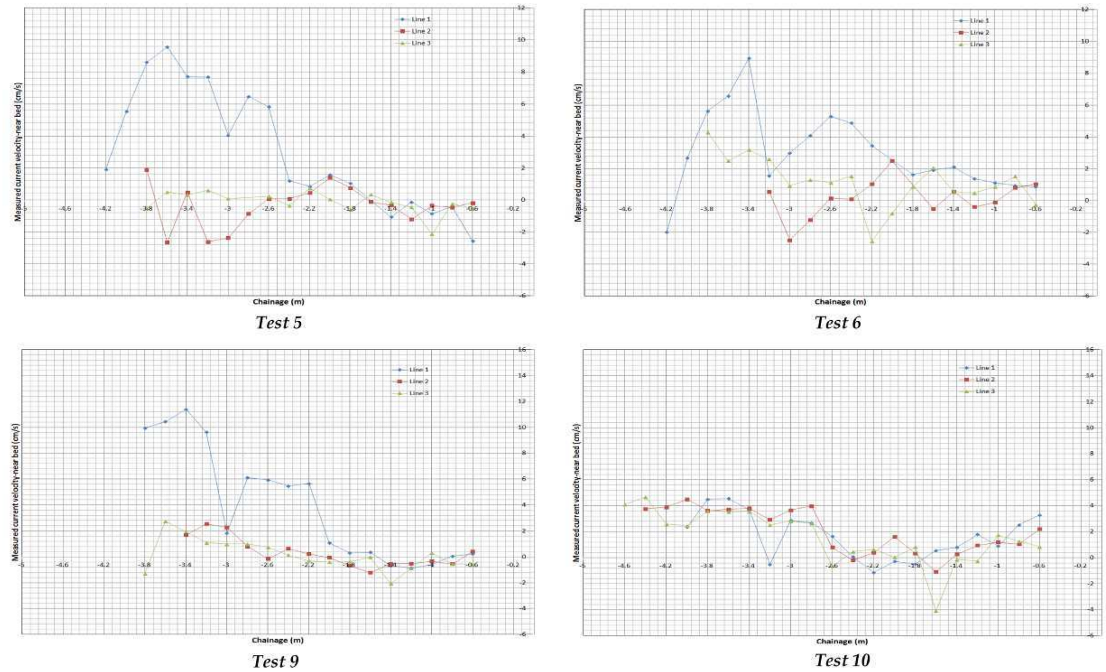

Figure 6. Cross-shore current velocity measurements near bed

In Figure 6, the reverse flow can be seen clearly at all lines for all tests. Most of the measurement points were before the breaking point but close enough so that the undertow current can be observed. The undertow was represented by the seaward direction of the currents. Though, it has to be mentioned that at some locations, the reverse current is replaced by a shoreward current. This behavior of currents was also observed from Test 4 to Test 10 (especially at uniform slope).

The cross-shore current velocities had high values, in contrast to the expectation of having very small or even zero values near the bed, even before the breaking point (for both shoreward and seaward directions).

The analysis of the wave-induced currents was divided into the along-shore and cross-shore currents. Both gravel and mixed beach had similar cross-shore and along-shore current velocities. However, it has to be mentioned that comparing the trench and the uniform slope beach, the trench had higher values of cross-shore current velocities for the mixed beach than the gravel beach and lower values of along-shore current velocities for the gravel beach than the mixed beach.

The along-shore current velocity profile was smoother in random waves than in regular (Antoniadis, 2009). This can be explained due to the fact that at random wave conditions the incoming waves have different heights, which result to their breaking at different water depths. Therefore, the along-shore driving force and the dissipation energy will be more distributed than during the regular wave conditions, when the distribution of the driving force is discontinuous at the breaking point.

The direction of the along-shore currents corresponded to the incoming wave direction, in the majority of the tests. The direction of along-shore currents at the trench, close to the breaking point, has shown a general trend of a return along-shore flow. This behavior could be caused by the turbulence generated on the trench after breaking or even by the reflection of waves at the trench. An important reason of this return along-shore flow could be the irregularity of the beach profile at the trench. Moreover, this return along-shore flow can be partly seen (before the breaking point) at the trench and the uniform slope, for both tests 1 and 2 (Antoniadis, 2009).

Visser (1991) identified a type of such a recirculation in six different types of wave basins as he was investigating the along-shore currents for regular waves. Nevertheless, this recirculation was only identified in the first two tests of the experiment and not in all tests, giving the impression that it could only be seen for the specific wave conditions of the first two tests. By observing the beach profile changing in these tests, for all lines, the creation of bars can be detected in Test 1, whereas in Test 2 bars were diminished. Thus, at Test 2 the recirculation was decreased compared to Test 1. The wave conditions in the first two tests were large and the breaking of the waves built up barred profiles and caused irregularities in the beach profile along the beach. This could have also created rip channels.

The irregular beach profile and the oblique waves might cause a wave-driven circulation current. An along-shore driving force similar to the conditions of a uniform coast will be exerted on the bar for waves that break, resulting in a creation of along-shore current on the bar. The along-shore current velocity could be strongly modified by the shoreward flux over the bar, and part of its along-shore momentum will be transferred to the flow in the trough. The flow in the trough could locally be stronger or weaker than the along-shore flow over the bar. This might feed the seaward flow in the rip channel and could create locally a flow against the incoming wave direction (Fredsoe and Deigaard, 1995).

In contrast with along-shore current velocity, cross-shore current velocity at the trench was different for both gravel and mixed beach (except Test 5 and Test 9). Furthermore, the cross-shore current velocity at the uniform slope was similar for both types of beach. Frequently the trench and the uniform slope had positive values of V_y. This pointed to an existence of a cross-shore flow with an offshore direction (reverse cross-shore flow).

The reverse flow can clearly be seen at all tests. Though, it has to be mentioned that at some locations, near the bed, the reverse current is replaced by a shoreward current. This behavior of currents was observed during Test 4 to Test 10 (especially at uniform slope). The shoreward direction of these currents also affected the sediment transport, as the sediment showed to be slightly moved shoreward at the locations influenced by these currents.

The cross-shore current velocity was expected to be very small, close to zero, near the bed. However, current velocities were not always zero or small (especially for regular waves). It was expected currents to have higher values close to the breaking point. However, during the tests currents had relatively high values (for both shoreward and seaward direction) even before the breaking point. The shoreward currents had a maximum value of about 5cm/s. The currents near the bed showed oscillating direction, from seaward to shoreward and vice versa, along the cross-shore section of the beach (from Line 1 to Line 3) showing behavior of an undertow current.

Lara et al. (2002), showed how the undertow behaves over a highly permeable bed. They conducted an experimental study in a laboratory, showing the mean flow characteristics over impermeable and permeable beds. Their study discussed the differences between water surface envelopes and undertow for these cases. They showed that in a permeable bed (D_{50}=19 and 39 mm) on the undertow there is a change of the velocity profile, with the magnitude of undertow close to the seafloor being reduced. This effect was more important in decreasing water depth and it was reduced for decreasing gravel size.

During Test 1 to Test 10, the sizes of D_{50} were 23mm and 12mm for gravel and mixed beach respectively, which are at the low range of the ones that were used in the experiments of Lara et al. (2002). The gravel beach is more permeable than the mixed beach, which sometimes tends to be impermeable. However, the undertow close to the bed was not reduced but it increased and was also replaced by a shoreward current, even outside the surf zone. This shoreward current could cause suspended sediment to be moved landward. This behavior of the undertow was more noticeable at the tests with the gravel beach. Comparing the magnitude of velocities between the gravel and mixed bed, it can be seen that the velocities were higher at the gravel bed, where the D_{50} was also the highest. This is in agreement with the observation of Lara et al. (2002).

Nevertheless, the increased magnitude and even the direction alteration of velocities near the bed, especially in the gravel bed, can be due to the mechanism of bed-generated turbulence. Lara et al. (2002) stated that the gravel bed-generated turbulence characteristics depend on the gravel size and increasing gravel size results in an increase in the velocity gradient, which is the principal mechanism for the generation of larger-scale turbulence over the gravel bed. This mechanism of bed-generated turbulence has been noticed by Buffin-Bélanger et al. (2000) and Shvidchenko et al. (2001) over gravel bed rivers resulting in Reynolds stresses that have different signs, revealing different vortex orientation (Lara et al., 2002).

In the surf zone, turbulence can be related, partly or even totally, to the wave breaking type. The turbulence generating mechanism is induced by the breaking process. The characteristics of turbulence structure and undertow are different in spilling and plunging breakers. Turbulent kinetic energy is transported seaward under the spilling breaker. This is different from the plunging breaker where turbulent kinetic energy is transported landward (Ting and Kirby, 1994).

Therefore, more experiments with different types of breaking, different water depths and different sizes of gravel and mixed (gravel and sand) could help in understanding this behavior of the undertow, in depth.

Cross-Shore Beach Profiles

The graphical presentation of the cross-shore profiles of all the tests and for all the three lines can be seen in Antoniadis (2009). Examples of the profile evolution of both types of beach, with random wave attack, are shown in Figure 7 to Figure 10.

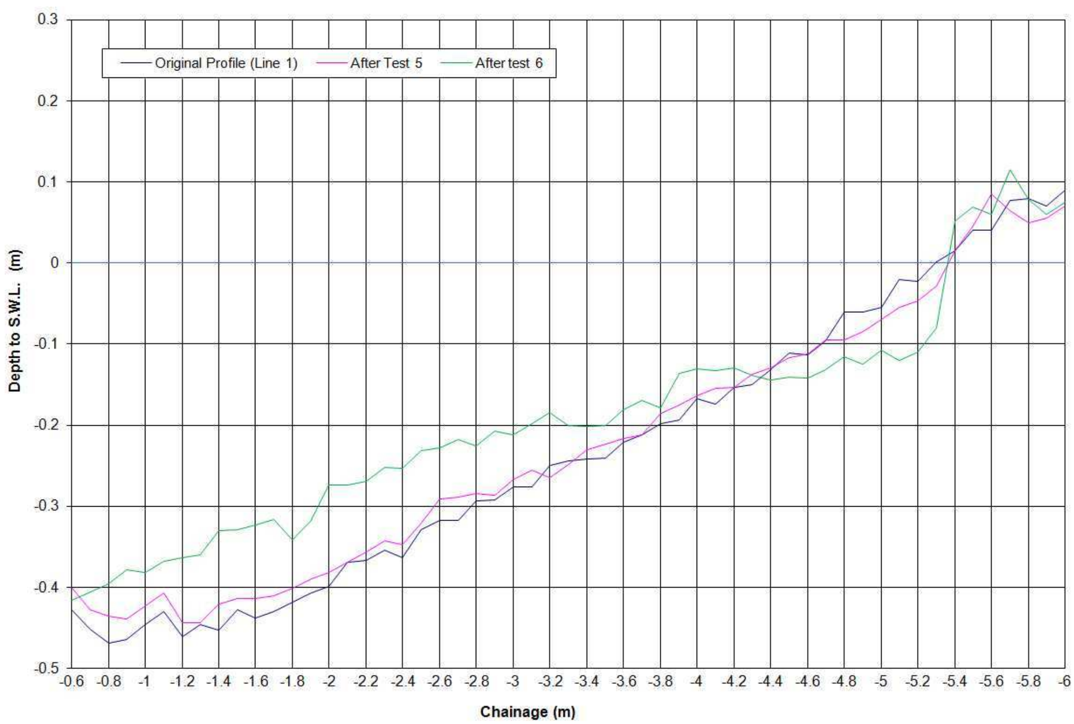

Figure 7. Cross-shore profile changes of trench during Test 5 and Test 6

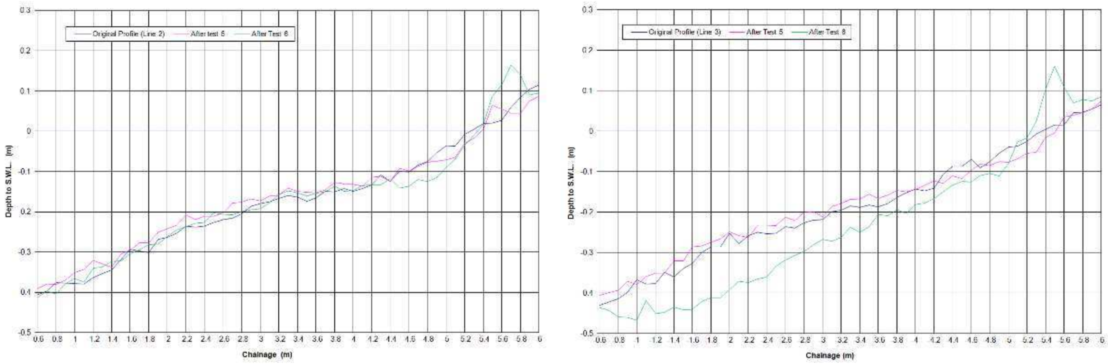

Figure 8. Cross-shore profile changes of uniform slope during Test 5 and Test 6

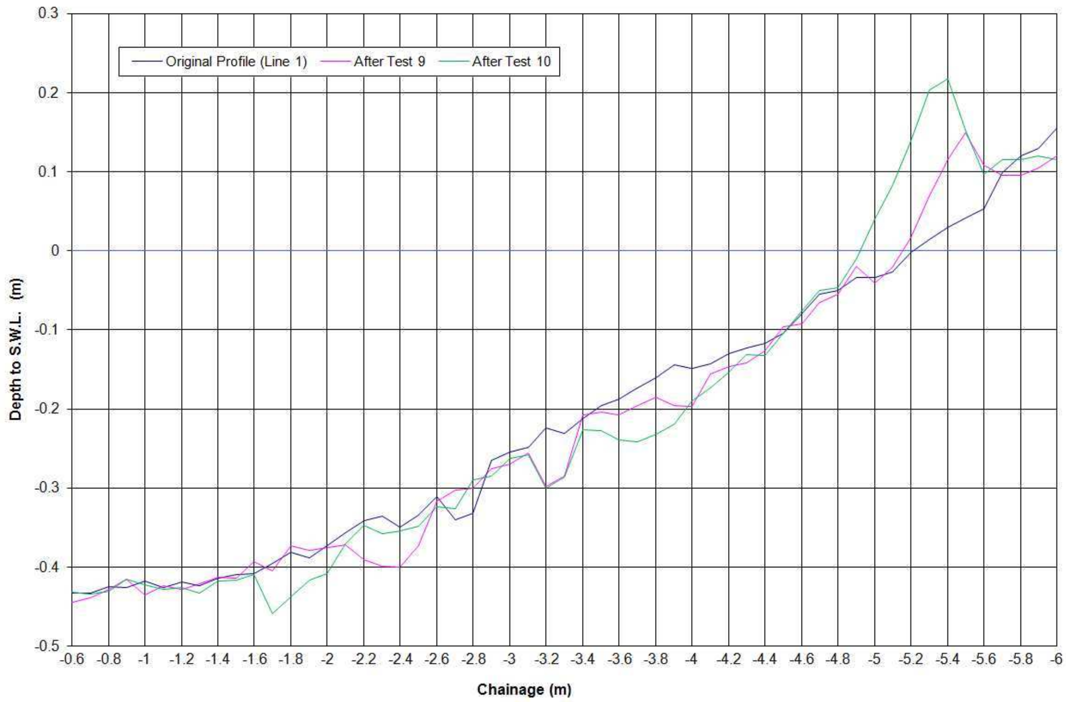

Figure 9. Cross-shore profile changes of trench during Test 9 and Test 10

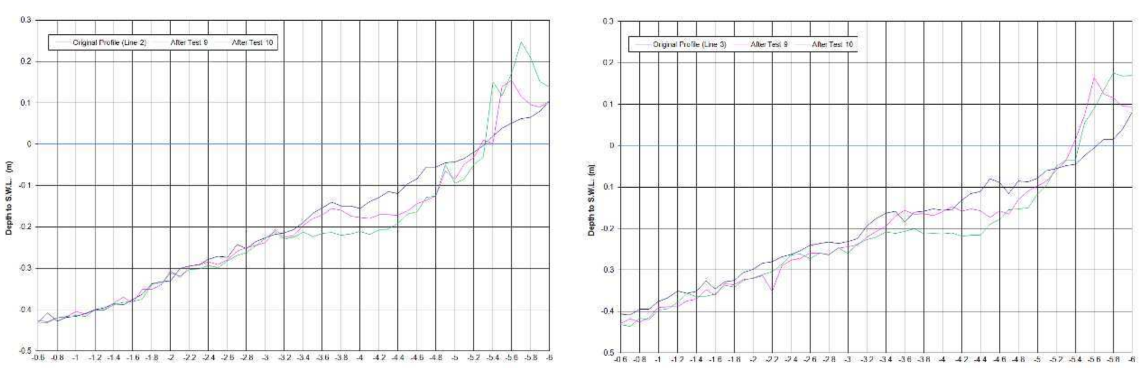

Figure 10. Cross-shore profile changes of uniform slope during Test 9 and Test 10

Figure 7 to

Figure 10 show that the response of the initial profile to the wave action, for both beaches, led to the built-up of material above the SWL (forming a crest, ridge or berm) and associated erosion below the SWL (near the breaking step). This behavior is a normal response of gravel beaches. Mixed beach developed quite differently than gravel beach. The difference was that the elevation of the crest was often, and especially for longer wave periods, slightly greater.

At Tests 5 and 6, Line 2 had low cross-shore sediment transport and led to the built-up of material above the SWL, forming a crest. However, at test 6, a high cross-shore sediment transport and a formation of a crest above SWL was noticed for Lines 3 and 1. It is worth noting that whereas Line 3 had its maximum erosion below SWL Line 1 had its maximum accretion below SWL This difference indicates that there is movement of sediment from Lines 3 to Line 1.

Considering Tests 9 and 10, there was a settlement of the sediment. At these tests, all three lines followed a similar pattern of bed level change having the highest form of crest (above SWL) at Test 10. The only difference between the lines was a small shift of the form of the crest which was related to the location of each line individually.

According to Powell (1990), an increase of the wave period for a given wave height (i.e. decreasing wave steepness H/L) results in the increase of the beach crest elevation and, as a consequence, the volume of material above the still water line. This is matched by a respective increase in the erosion of the beach profile below the step position, and therefore a seaward displacement of the lower limit of profile deformation. This is the case for the gravel beach (

Figure 7 to

Figure 8) and for mixed beach (

Figure 9 to

Figure 10).

Beach Profile Response

The beach profile response to wave action and especially in storm events is very important because storm events dominate erosion. Powell (1990) noticed that the profile of gravel beaches steepen during storms due to crest build up. Lopez de San Roman Blanco (2003) observed that the bed step is formed inshore at the location of the breaking waves, due to erosion, where the crest is formed further onshore due to accretion. The size of the active beach profile affected depends on the magnitude of wave action. This behavior of the gravel beach profile was observed during the first two tests for both trench and uniform slope. However, the beach with the uniform slope shows higher erosion below and above SWL and the crest was slightly formed further onshore. On the contrary, at trench, the beach profile was slightly eroded below the SWL and accretion occurred above SWL formed the highest crest along the beach. This discrepancy is explained by the along-shore sediment transport occurred by the oblique wave action. As a result, there was erosion at the uniform slope beach and the beach material was transported and built-up at the trench area. Similar behavior was observed in Test 4 and also during tests with the mixed beach.

The response of the initial profile of the mixed beach to the wave action led to the built-up of material above SWL and associated erosion below SWL showing similarities with the behavior of a gravel beach. However, the mixed beach developed quite differently than the gravel one. The main morphological differences can be seen at random wave conditions. These were:

- The crest for the mixed beach was of much higher elevation compared to the gravel beach. This behavior is explained by the fact that mixed beaches dissipate less energy through infiltration (less permeable) than the gravel beach, and as a result the run-up will be higher affecting consequently the crest elevation.

- The extent of the onshore movement is greater than that of gravel beaches. This is in contrast with the conclusions of Lopez de San Roman Blanco (2003)
- The step formation was easier to locate for the mixed beach, rather than the gravel beach.
- The erosion below the SWL was larger for the mixed beach compared to the gravel beach. This is the result of the settlement of the sand and also its movement offshore.
- Irregularities in the profile (especially at the trench) were larger for the mixed beach.
- The mobility of the mixed beach is greater in comparison to gravel beach. This is in contrast with the conclusions of Lopez de San Román Blanco (2003).

Sediment Balance

The results of the sediment balance of the uniform slope and the trench were divided into two categories: *total sediment balance* and *sediment balance below and above SWL*. In both categories the sediment balance is presented along each line, at the end of each test, for gravel and mixed beach, respectively. The following figures were calculated for each test, and shown in Table 5 to

Table 8;

- Accretion: indicates total positive volumetric change along each line
- Erosion: indicates total negative volumetric change along each line
- Total: indicates total volumetric change along each line (sum of Accretion and Erosion)
- Difference (%): indicates the relative difference between the accretion and erosion. It also accounts for the conservation of sediment volume and therefore gives an idea of the amount of compaction and settlement that occurred in each line and test (Lopez de San Roman-Blanco, 2003). This parameter is calculated by:

Eq. 2 $$\mathbf{Difference\ (\%)} = \frac{\mathbf{Accretion - Erosion}}{\mathbf{Total}} \mathbf{x100}$$

It is important to find out if gravel acts like a filter for sand or not. The filter acts like a barrier for the fine material preventing it to pass through the voids of the filter. Based on the soil category "for sand and gravels", the filter criteria by USBR (1994) was $D_{15F} \leq 4D_{85B}$, where D_{15F} indicates the grain size diameter of the filter in which 15% by weight of the soil particles are smaller in diameter, and D_{85B} indicates the grain size diameter where 85% of the base or filter soil is smaller in diameter. For the current experiment D_{15F}=16.66mm > 4*D_{85B}=2.4mm. This shows that gravel did not act as a filter for sand.

The results for the total sediment balance investigation are listed in Table 5 and

Table 6 where the results for the sediment balance below and above SWL investigation are listed in

Table 7 and

Table 8. Despite the fact that the number of waves between each test is different, it will not change the trend of the parameters.

Table 5. Total sediment balance of uniform slope

	Line 3				Line 2			
	Accretion (m^3)	Erosion (m^3)	Total (m^3)	Difference (%)	Accretion (m^3)	Erosion (m^3)	Total (m^3)	Difference (%)
Test 1	0.04	0.1775	0.2175	-63.22	0.0001	0.3383	0.3384	-99.94
Test 2	0.1163	0.2348	0.3511	-33.75	0.0627	0.0822	0.1449	-13.46
Test 3	0.0643	0.0063	0.0706	82.15	0.0323	0.0206	0.0529	22.12
Test 4	0.0103	0.0194	0.0297	-30.64	0.0298	0.0189	0.0487	22.38
Test 5	0.0643	0.0312	0.0955	34.66	0.0716	0.0238	0.0954	50.10
Test 6	0.0601	0.3408	0.4009	-70.02	0.0348	0.0742	0.109	-36.15
Test 7	0.1049	0.011	0.1159	81.02	0.013	0.0827	0.0957	-72.83
Test 8	0.0122	0.0712	0.0834	-70.74	0.0479	0.0318	0.0797	20.20
Test 9	0.0634	0.1098	0.1732	-26.79	0.0361	0.0814	0.1175	-38.55
Test 10	0.0297	0.0893	0.119	-50.08	0.0498	0.0676	0.1174	-15.16

Table 6. Total sediment balance of trench

	Line 1			
	Accretion (m^3)	Erosion (m^3)	Total (m^3)	Difference (%)
Test 1	0.0592	0.0327	0.0919	28.84
Test 2	0.1016	0.1122	0.2138	-4.96
Test 3	0.0623	0.0052	0.0675	84.59
Test 4	0.0192	0.0294	0.0486	-20.99
Test 5	0.0584	0.0242	0.0826	41.40
Test 6	0.2307	0.0386	0.2693	71.33
Test 7	0.0304	0.0497	0.0801	-24.09
Test 8	0.069	0.018	0.087	58.62
Test 9	0.0436	0.0742	0.1178	-25.98
Test 10	0.1063	0.0482	0.1545	37.61

Table 7. Sediment balance below SWL of uniform slope

	Line 3				Line 2			
	Accretion (m^3)	Erosion (m^3)	Total (m^3)	Difference (%)	Accretion (m^3)	Erosion (m^3)	Total (m^3)	Difference (%)
Test 1	0.0284	0.1507	0.1791	-68.29	0.0001	0.2618	0.2619	-99.92
Test 2	0.1163	0.1695	0.2858	-18.61	0.0414	0.0822	0.1236	-33.01
Test 3	0.0535	0.0063	0.0598	78.93	0.0148	0.0206	0.0354	-16.38
Test 4	0.0066	0.0158	0.0224	-41.07	0.0165	0.0149	0.0314	5.10
Test 5	0.0625	0.0291	0.0916	36.46	0.0654	0.0131	0.0785	66.62

Test 6	0.0146	0.3408	0.3554	-91.78	0.002	0.0742	0.0762	-94.75
Test 7	0.0792	0.011	0.0902	75.61	0.0065	0.0769	0.0834	-84.41
Test 8	0.01	0.0572	0.0672	-70.24	0.0257	0.0317	0.0574	-10.45
Test 9	0.0112	0.1098	0.121	-81.49	0.0066	0.0808	0.0874	-84.90
Test 10	0.0121	0.0788	0.0909	-73.38	0.0037	0.0665	0.0702	-89.46

Table 8. Sediment balance below SWL of trench

	Line 1			
	Accretion (m^3)	**Erosion (m^3)**	**Total (m^3)**	**Difference (%)**
Test 1	0.0405	0.0253	0.0658	23.10
Test 2	0.0276	0.1122	0.1398	-60.52
Test 3	0.0508	0.0046	0.0554	83.39
Test 4	0.0169	0.0217	0.0386	-12.44
Test 5	0.0539	0.0174	0.0713	51.19
Test 6	0.2186	0.0375	0.2561	70.71
Test 7	0.0077	0.0497	0.0574	-73.17
Test 8	0.0372	0.0167	0.0539	38.03
Test 9	0.0121	0.0673	0.0794	-69.52
Test 10	0.0525	0.0475	0.1	5.00

The behavior of the sediment balance at the uniform slope was not linear for both types of beach. It was likely based on the oblique wave attack and the influence of the cross-shore and along-shore sediment transport. The total volumetric changes for the gravel beach were in the order of 39-65% to those of the mixed beach, for the same wave conditions. This indicates the greater mobility of the mixed beach in comparison to the gravel beach. This is in contrast with the conclusions of Lopez de San Roman-Blanco (2003). It also shows that this difference in total volumetric change between gravel and mixed beaches is inversely proportional to the wave height.

Relative difference between accretion and erosion for the gravel beach varied between -99.94% to +82.15%, respectively. These relative differences for the case of mixed beach were negative most of the time and can be as much as 70%, indicating that sediment volume was not conserved. This could be caused by the settlement of the beach material and its compaction due to wave action. The sand settled down deeper in the beach where the gravel, composing the accreting material, was deposited above the SWL, forming the beach crest.

As far as the trench is concerned, the total volumetric changes for the gravel beach were of the order of 45% to those of the mixed beach, for the same wave condition. This indicates the greater mobility of the mixed beach, in comparison to the gravel beach. It also shows that this difference in total volumetric change between gravel and mixed beach is inversely proportional to the wave height.

Relative difference between accretion and erosion for the gravel beach varied between -20.99% to +84.59%, respectively. These relative differences in the case of mixed beach are negative in the first test and positive for the following tests. Its relative difference vary between -24.09% to +58.62%, respectively.

CONCLUSION

The main aim of the present paper was to present the results of an experiment relating to a 1:1 scale 3D physical model that took place at the 3-D wave basin located at Franzius-Institute (Marienwerder) of University of Hannover. The experiment was an investigation of the hydrodynamics and the cross-shore sediment transport of gravel and mixed beaches evolved by oblique wave attack. An examination of the influence of a feature (trench) in their behavior was also carried out.

The analysis of the cross-shore currents in both gravel and mixed beaches focused on the behavior of the undertow (reverse flow) and especially its behavior near the bed. The undertow was observed in both trench and uniform slope for both types of beach. However, near the bed, the trench had higher values of undertow flow compared to the uniform slope beach, and also the undertow showed higher values than the mixed beach compared to the gravel beach.

The cross-shore currents near the bed, for both gravel and mixed beaches, showed no reduction in their values and depicted an oscillatory pattern in direction, from seaward to shoreward and vice versa, along the cross-shore section of the beach. This behavior, including the case where the value of the cross-shore current velocity increased instead of being decreased, can be caused from the permeability of the beach and also the mechanism of the bed-generated turbulence. It influenced the cross-shore sediment transport at the bed and it is more noticeable at the gravel beach due to its higher permeability compared to the mixed beach.

As far as the behavior of the along-shore currents is concerned, an along-shore flow having different direction to the incoming waves was observed, for both gravel and mixed beaches at the trench. This behavior could be due to the reflected waves generated at the trench and is more likely due

- The step formation was easier to locate for the mixed beach rather than the gravel beach.
- The erosion below the SWL was larger for the mixed beach compared to the gravel beach. This is the result of the settlement of the sand and also its movement offshore.
- Irregularities in the profile (especially at Line 1) were larger for the mixed beach.
- The mobility of the mixed beach is greater in comparison with gravel beach. This is in contrast with the conclusions of Lopez de San Román Blanco (2003).

Data from measurements of the cross-shore profile, current velocities (at directions x, y and z) along the beach with uniform slope and a trench for identical wave conditions for a gravel and mixed (sand and gravel) beach are available to other research groups.

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to the fact that the irregular beach profile of the trench with the combination of the oblique waves a wave-driven circulation current has been created leading to the this return along-shore current. At the uniform slope beach this return along-shore current was observed before the breaking point during the first two tests where there were the highest wave conditions of the experiment. However, in the case of the return flow, that could be explained by the creation of potential rip currents at that location.

Moreover, the main morphological differences between gravel and mixed beach during the experiment were:

- The crest for the mixed beach was of much higher elevation compared to the gravel beach. This behavior is explained by the fact that mixed beaches dissipate less energy through infiltration (less permeable) than a gravel beach and as a result the run-up will be higher and consequently the crest elevation.
- The extent of the onshore movement is greater than that of gravel beaches. This is in contrast with the conclusions of Lopez de San Roman Blanco (2003)

Cardiff University and by staff of Franzius-Institute (Marienwerder) of University of Hannover.

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