CHAPTER 79

VELOCITY AND SEDIMENT CONCENTRATION FIELDS ACROSS SURF ZONES

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Abstract

Wave-induced currents and sediment concentrations in suspension across the surf zone were investigated at prototype scale in the BIG WAVE FLUME in Hannover for combined beach and dune profiles as well during the development phase until quasi-equilibrium stage as after beach equilibrium conditions had been reached. The selected initial profiles were partly investigated in repeated tests with regular and irregular waves. Based upon the obtained experimental data a comparison is presented between the measured and calculated landward displacement of sediment volume through a selected point on the beach into seaward areas. The discrepancies in between the results for measured profile change and for calculated sediment transport volume derived from vertical current and suspension distributions are discussed.

Introduction

The description of coastal processes in the surf zone depends upon the understanding of interactions between the beach profile and the breaking waves, the wave-induced currents, and the associated movements of beach material. In order to calculate the net cross-shore sediment transport it is necessary to describe both the horizontal orbital velocity field $u(x, z, t)$ and the sediment concentration field $c(x, z, t)$ in space and time. As it is very difficult to measure these parameters under storm conditions in the field, prototype tests were carried out in the BIG WAVE FLUME in Hannover in order to study these processes at essentially full scale. In the paper first results of measurements on suspended sediment concentrations and wave-induced currents on beaches are presented.

Scope of Investigations

Two test series were carried out in the BIG WAVE FLUME, which is 324 m long, 7 m deep and 5 m wide. The initial profiles - illustrated in Fig. 1 - were called "dune without foreshore" (a) and "dune with foreshore" (b):

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(a) + 2 m above still water level (SWL) and 30 m wide dune with a 1 to 4 seaward slope down to channel floor (- 5 m)

(b) + 2 m above SWL and 10 m wide dune with 1 to 4 seaward slope down to 1 m below SWL and following 1 to 20 slope down to channel floor.

Both profiles were subjected to regular wave attack ($\bar{H} = H_{rms} = 1.5$ m, T = 6 s, d = 5.0 m). The similarity index using the initial profile and $H_0/L_0 = 0.04$ yielded $\xi_0 = 1.48$ (dune without foreshore) and $\xi_0 = 0.29$ (dune with foreshore). Additionally to these tests with regular waves the dune without foreshore experiments were repeated with irregular waves (JONSWAP-Wave-Spectrum, $H_{1/3} = 1.5$m, $T_p = 6$ s, d = 5.0 m).

The sand used had a mean diameter $D_{50} = 330$ µm and geometric standard deviation of $\sigma_g = 1.47$.

The experiments were carried out by increments of up to 80 waves as by then the initial wave form became significantly affected by reflection. Therefore, the test series was interrupted and restarted after the water had come to rest; the interval was used for the profile levelling.

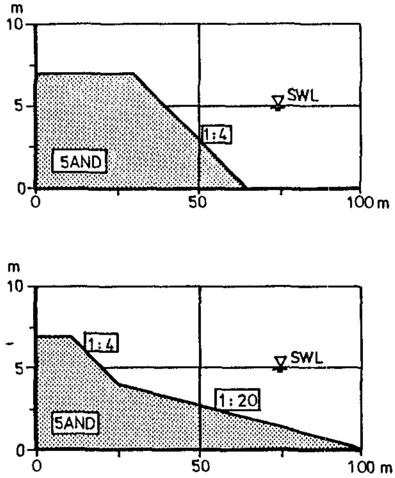


Figure 1. Initial beach profiles: Dune without foreshore (above) and dune with foreshore (below).

The tests with regular waves were stopped whenever the wave height variation reached ± 20 % of the originally generated wave height. Above this limitation it was observed in preceding tests that the breaker-line started to move from its original position. The experiments with the JONSWAP-Wave-Spectrum were interrupted after three repetition intervals totalling nearly 12 minutes.

Sediment Concentration at Equilibrium Profile

Samples of the material suspended due to wave action were extracted by pumps at elevations from 0.02 m to 1.0 m above the bed at selected positions within the surf zone. The prototype of the pumping-system was developed by the DELFT HYDRAULICS LABORATORY (BOSMAN, 1986). The extraction nozzles (diameter: 3 millimeter) were fixed on a vertical pipe and orientated horizontally and perpendicularily to the flow direction of wave-induced currents. The intake-velocity at the nozzle reached about 1.0 m/s which was approximatly equal to the orbital velocities.

The samples were taken during each test increment at one fixed position on the beach profile without taking into consideration the method of bed averaging extraction as suggested by BOSMAN (1986) derived from small scale test in order to eliminate the effects of bed features.

Dune without Foreshore

Results due to Regular Waves

The results presented in the following are thus time-averaged data each from a sequence of about 80 waves (8 minutes). Fig. 2 illustrates suspension distributions over the equilibrium profile (dune without foreshore, Fig. 1 above) at four positions within the breaker zone at different points within the surf zone.

Generally it can be stated from the test results:

- the maximum suspension rate was recorded near the crest of the bar
- in the offshore direction and shoreward of the bar the sediment concentration decreased remarkably
- the breaking-point approximately coincided with the crest of the bar
- the breaker type on the quasi-equilibrium profile, which developed from 1 to 4 slope of the dune without foreshore was the plunging breaker
- the averaged wave heights at the measuring points (A to D) were: $\bar{H}_A$ = 0.8 m, $\bar{H}_B$ = 0.8 m, $\bar{H}_C$ = 1.6 m and $\bar{H}_D$ = 1.9 m
- the water-depths were: d_A = 0.96 m, d_B = 1.48 m, d_C = 1.25 m and d_D = 1.60 m

In Table 1 the sediment concentration data from the investigations at the dune without foreshore with regular waves are summarized.

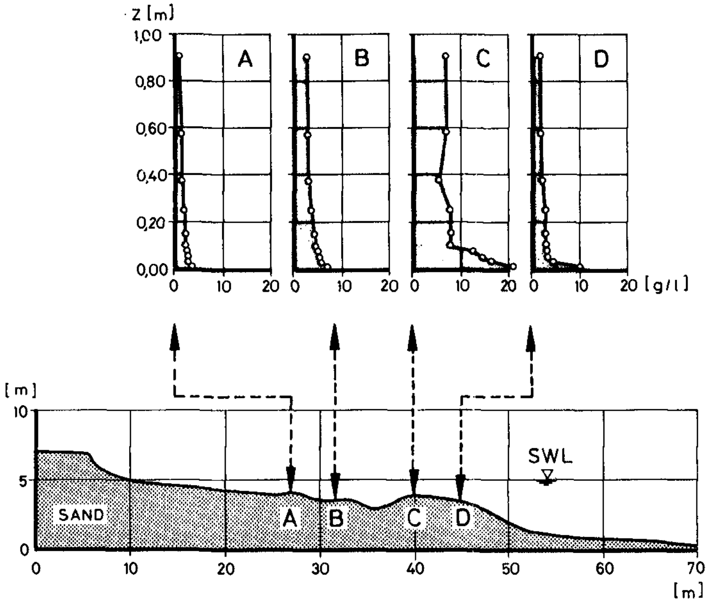


Figure 2. Suspension distributions on the beach at quasi-equilibrium profile conditions due to regular waves for the test series: "dune without foreshore"

Table 1. Sediment concentration data due to regular waves for the test series: "dune without foreshore"

DUNE WITHOUT FORESHORE REGULAR WAVES		H = 1.5 m		T = 6 s
Height above bottom	Sediment Concentration $\bar{c}$	$\bar{c}$	$\bar{c}$	$\bar{c}$
m	g/l	g/l	g/l	g/l
0.02	3.3	7.1	21.0	9.9
0.04	2.9	5.9	16.3	4.6
0.06	2.7	5.5	14.6	3.5
0.085	2.5	5.1	12.6	3.3
0.11	2.2	4.6	7.9	3.1
0.16	2.3	4.7	8.2	3.0
0.26	2.0	3.7	8.0	3.0
0.385	1.6	3.1	5.5	2.3
0.585	1.4	3.1	7.2	1.8
0.91	1.0	2.9	7.0	1.9
Location	A	B	C	D

Results due to JONSWAP-Wave-Spectrum

The sediment concentration data are time-averaged values over three-times the spectrum-repetition-interval (nearly 12 minutes) which is equal to 125 times the peak period T_p = 6 s. Similar to the results for the beach profile due to regular waves, the maximum sediment concentration was observed shoreward of a so-called step in the beach profile (Fig. 3). The breaker zone varied in between 38 m and 15 m from the

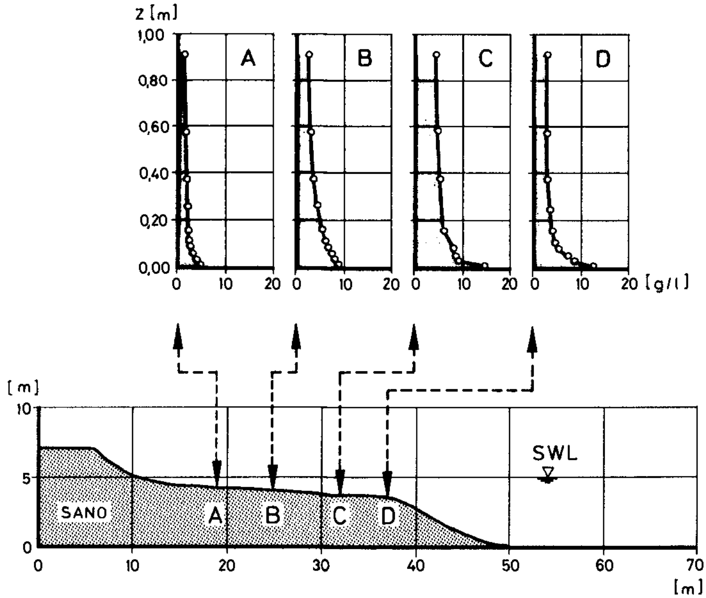


Figure 3. Suspension distributions on the beach at quasi-equilibrium profile conditions due to JONSWAP-Wave-Spectrum for the test series: "dune without foreshore"

shoreline. The significant wave heights at the points A to D were as follows: A: $H_{1/3}$ = 1.0 m, B: $H_{1/3}$ = 1.2 m,
C: $H_{1/3}$ = 1.7 m, D: $H_{1/3}$ = 1.5 m.

The water depths were as follows: d_A = 1.0 m, d_B = 1.15 m, d_C = 1.45 m, d_D = 1.75 m.

Table 2 gives the sediment concentration data associated to the JONSWAP-Wave-Spectrum and the test series "dune without foreshore".

Table 2. Sediment concentration data due to JONSWAP-Wave-Spectrum for the test series: "dune without foreshore"

DUNE WITHOUT FORESHORE JONSWAP-WAVE-SPECTRUM $H_{1/3}$ = 1.5 m T_p = 6 s				
Height above bottom	Sediment Concentration			
	$\bar{c}$	$\bar{c}$	$\bar{c}$	$\bar{c}$
m	g/l	g/l	g/l	g/l
0.02	6.2	9.5	15.4	13.0
0.04	4.6	8.6	9.1	9.0
0.06	3.9	8.0	-	8.0
0.085	3.5	7.1	8.7	6.5
0.11	3.0	6.7	7.3	5.2
0.16	2.8	6.3	6.3	4.8
0.26	2.5	4.2	-	4.3
0.385	2.1	3.6	5.3	3.1
0.585	1.8	3.2	4.9	2.9
0.91	1.3	2.8	4.0	2.7
Location	A	B	C	D

Dune with Foreshore

Results due to Regular Waves

The sediment concentration data obtained over the quasi-equilibrium profile which developed from the dune with foreshore are time-averaged values from a sequence of about 70 waves (7 minutes). The breaker type over the equilibrium profile was the plunging breaker due to the steep seaward slope of the bar. The breaking point was approximately located near the crest of the bar. The averaged wave heights at the points A to C yielded:

$$\bar{H}_A = 1.1 \text{ m},\ \bar{H}_B = 1.5 \text{ m},\ \bar{H}_C = 2.1 \text{ m}$$

The water depths were: d_A = 1.95 m, d_B = 1.4 m and d_C = 2.6 m.

Fig. 4 illustrates the suspension distribution over the equilibrium profile and in Table 3 the measured data are summarized.

The Accuracy of Concentration Measurements

The accuracy of the measured concentrations depends significantly upon the kind of the selected measuring system and upon the suitablity of system to be used in the laboratory or in the prototype. BOSMAN (1986) recommends on the basis of extensive investigations the TABAC method which means Time-And-Bed-Averaged-Concentration.
BOSMAN (1986) writes:

> The "effect on the local concentration is purely random and can be reduced by averaging either over space or over time".

For the prototype investigations in the BIG WAVE FLUME the time-averaging method was applied by means of a stationary pump system with which suspended sediment samples over 7 to 12 minutes were extracted.

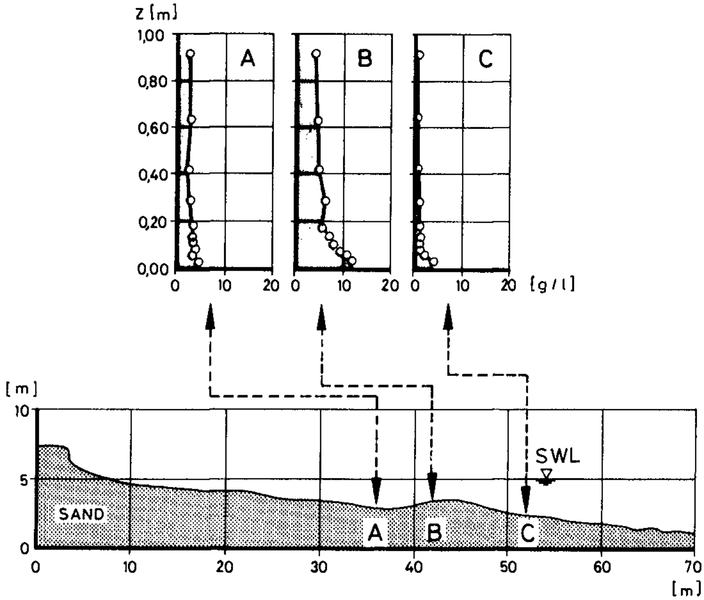
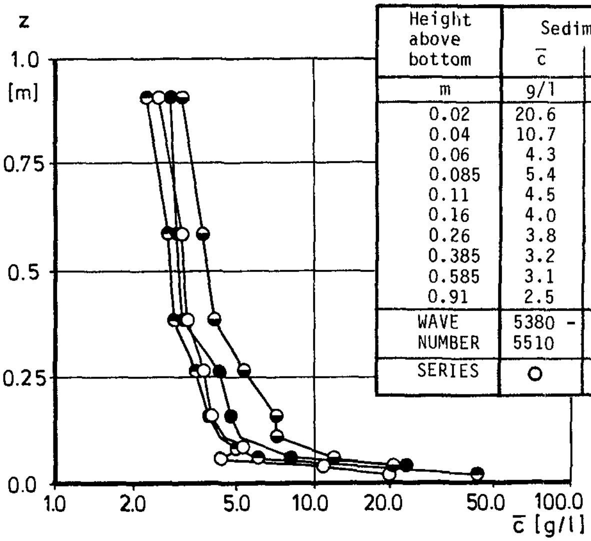


Figure 4. Suspension distributions on the beach at quasi-equilibrium profile conditions due to regular waves for the test series: "dune with foreshore"

Table 3. Sediment concentration date due to regular waves for the test series: "dune with foreshore"

DUNE WITH FORESHORE REGULAR WAVES	H = 1.5 m		T = 6 s
Height above bottom	Sediment Concentration $\bar{c}$	$\bar{c}$	$\bar{c}$
m	g/l	g/l	g/l
0.04	4.7	11.9	4.2
0.06	3.0	10.8	2.1
0.08	4.0	9.4	1.8
0.105	3.6	8.0	1.2
0.13	3.2	7.4	1.4
0.18	3.4	6.0	1.4
0.28	3.1	6.2	0.9
0.405	2.7	5.0	0.9
0.605	2.9	4.7	0.7
0.93	2.7	4.0	0.4
Location	A	B	C

In order to illustrate the range of scattering at one position at quasi-equilibrium condition Fig. 5 shows the results of 4 repeated measurements due to JONSWAP-Wave-Spectrum for the test series "dune without foreshore".



Height above bottom	Sediment Concentration			
	$\bar{c}$	$\bar{c}$	$\bar{c}$	$\bar{c}$
m	g/l	g/l	g/l	g/l
0.02	20.6	43.6	42.4	19.7
0.04	10.7	23.0	16.7	20.8
0.06	4.3	8.0	6.1	11.9
0.085	5.4	6.5	4.9	9.1
0.11	4.5	5.2	4.3	7.1
0.16	4.0	4.8	3.9	7.1
0.26	3.8	4.3	3.5	5.5
0.385	3.2	3.1	2.9	4.1
0.585	3.1	2.9	2.7	3.7
0.91	2.5	2.7	2.2	3.0
WAVE NUMBER	5380 - 5510	5510 - 5640	5640 - 5770	5770 - 5900
SERIES	○	●	◒	◓

Figure 5. Repeated concentration measurements at the same position over the quasi-equilibrium profile developed from the dune without foreshore and JONSWAP-Wave-Spectrum

Near the bed the mean value of concentration from 4 measurements is $\bar{c} = 30 \pm 10$ g/l (approx. $\pm$ 30 %), at a position nearly 1.0 m above the bed the sediment concentration was about $\bar{c} = 3 \pm 1$ g/l (approx. $\pm$ 30 %).

This example of varying suspended sediment concentration may illustrate the problem of "accuracy". Even in laboratory at a prototype scale, i.e., in the BIG WAVE FLUME a stable equilibrium beach profile and constant measuring data cannot be expected. In all tests it was observed that the profile shape fluctuates and that the location of each breaker influences the concentration in a random way and thus the net sediment transport in the surf zone.

Velocity Fields in the Surf Zone

The measurements of wave-induced on-/offshore currents were carried out simultaneously at several fixed positions within the surf zone. Records were obtained from 0.1 m up to 0.6 m above the actual sand bed at the dune without foreshore and up to 1.0 m at the dune with foreshore. The single velocities are time-averaged values obtained from a single test increment (7 to 12 minutes). Fig. 6 shows as an example the distribution of wave-induced on-/offshore currents measured in the surf zone over the equilibrium profile from dune without foreshore and the JONSWAP-Wave-Spectrum. The difference between the averaged seaward and shoreward velocities $\bar{u}$ yields the net velocity u_R.

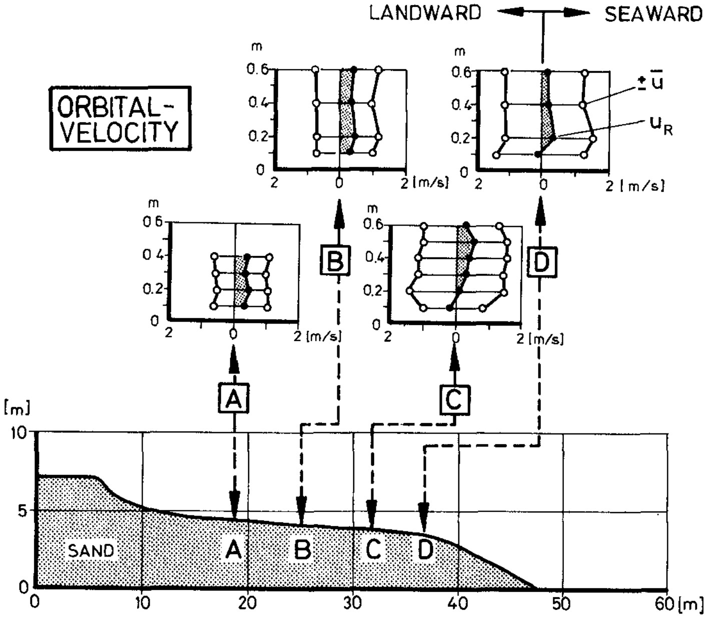


Figure 6. Time-averaged on-/offshore currents due to JONSWAP-Wave-Spectrum over the quasi-equilibrium of the dune without foreshore test series

Table 4 shows the averaged values of the recorded velocities with electromagnetic current meter due to the JONSWAP-Wave-Spectrum. The seaward direction is assumed as positive axis.

Table 4. Time-averaged on-/offshore currents across the surf zone due to JONSWAP-Wave-Spectrum at the dune without foreshore

DUNE WITHOUT FORESHORE JONSWAP-WAVE-SPECTRUM				$H_{1/3}$ = 1.5 m				T_p = 6 s				
Height above bottom	Time-averaged on-/offshore currents											
	+u	-u	u_R	+u	-u	u_R	+u	-u	u_R	+u	-u	u_R
m	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s
0.1	0.96	0.63	0.33	1.04	0.73	0.31	0.84	1.00	-.16	1.31	1.34	-.03
0.2	0.99	0.57	0.42	1.18	0.70	0.48	1.45	1.27	0.18	1.46	1.13	0.33
0.3	0.96	0.62	0.34	-	-	-	1.48	1.12	0.36	-	-	-
0.4	1.01	0.66	0.35	1.05	0.71	0.34	1.56	1.13	0.43	1.31	1.11	0.20
0.5	-	-	-	-	-	-	1.56	0.97	0.59	-	-	-
0.6	-	-	-	1.14	0.74	0.40	1.31	1.03	0.28	1.29	1.16	0.13
Location	A			B			C			D		

The location of the breaker zone, the significant wave heights and water depths at the points of measurements (A to D) are documented in the previous chapter.

Cross-Shore Sediment Transport Rate

The sediment volume passing at one position of the beach profile which developed from dune with foreshore from shoreward to seaward location is used in the following to compare calculated and measured data to discuss the reliability and to point out the order of magnitude of the sediment transport rates obtainable by means of this method.

Sediment passing a given Location of the Beach

The measurements were carried out after 50 waves had already run on the initial profile of the dune with foreshore. At this stage (after 50 waves) the beach profile was surveyed (= initial profile) and then another 80 waves were run. During this time sediment concentration samples were extracted at a location of x = 26 m from the shoreline and 2.0 m apart from the side wall of the flume. Afterwards the profile was resurveyed in three profiles of the 5 m wide flume, in the centre-line and 1.5 m to either side as basis for the calculation of removed sediments. During the test run the water depth at the point of measurement remained constant with d = 1.9 m. The averaged wave height of the regular waves was $\bar{H}$ = 1.3 m.

Cross-Shore Current

The velocities were measured at the same location (x = 26 m) in the middle of the channel, at elevations between 0.1 m to 1.0 m above the bed. The velocity at one elevation was measured over each increment of 70 waves. It was assumed that during consecutive test increments up to a total of 760 waves the velocities at the selected elevations remained more or less constant. The measured net velocity distribution is illustrated on Fig. 7. It is seen that the seaward column (below 1 m over the bed) is approximately constant at $\bar{u}_R$ = 0.53 m/s. The standard deviation of the measured values was σ = 0.11.

Suspended Sediment

Due to the high turbulence, particulary at macro scale, in the surf zone the sediment moves in whirls and clouds. Therefore no separation of suspended-load and bed-load was made for the following analysis. The measured vertical profile of the suspended sediment was fitted to the exponential function as suggested by v.d.GRAAFF and ROELVINK (1984). Table 5 shows the measured and calculated data together with the computed bottom concentration c_o.

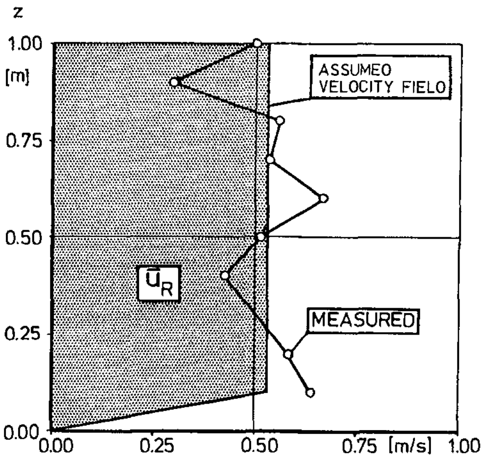


Figure 7. Distribution of the measured data u_R and assumed velocity profile $\bar{u}_R$ for calculation

Table 5. Measured and calculated sediment concentration data

Height above bottom	Sediment Concentration $\bar{c}_{meas.}$	$\bar{c}_{calc.}$
m	g/l	g/l
0.02	(5.93)	8.88
0.04	13.20	8.00
0.06	10.50	7.25
0.085	8.53	6.49
0.11	6.25	5.86
0.16	5.77	4.93
0.26	5.34	3.83
0.385	4.40	3.17
0.585	3.60	2.72
0.91	2.89	2.41
Bottom concentration:		c_o = 9.95 g/l

Net On-/Off-Shore Transport

The net sediment transport was calculated with the total transport formula:

$$S = \int_0^z c\ (z,t) \cdot u\ (z,t) \cdot dz \qquad (1)$$

which for the present case may be written as

$$\dot{S} = \int_0^z \bar{c}_{cal} \cdot \bar{u}_R \cdot dz \qquad (2)$$

The time-averaged sediment movement seaward past the measuring position during the initial test increment of 80 waves was calculated from the superposition of the beach profiles before and after the test run and referred to 1 m width of beach. The result yielded a volume of $A = 1.14\ m^3/m \pm 30\ \%$. The suspended sediment transport was calculated with the data in Table 5 to $\dot{S} = 1.57$ kg/s or $S \approx 0.45\ m^3/m \pm 30\ \%$. From this comparison a difference of 60 percent between measurement and computation is obtained, this is less than one order of magnitude. Fig. 8 illustrates for the point of measurement the relevant data for the analysis.

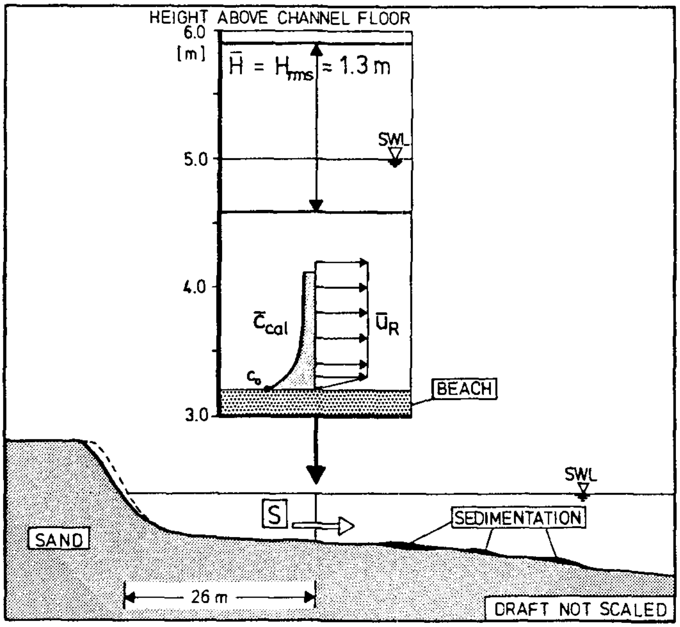


Figure 8. Schematic layout of applied data at the point of measurement for comparison of sediment transport during a test increment of 80 waves

With respect to discrepancies it has to be pointed out that the sediment concentration was measured only up to 0.91 m above the bed which is only 48 percent of the total water depth of d = 1.9 m. From visual observation it was obvious that suspended sediment were moved up to the water surface in the presence of large eddies (Fig. 9 and 10).

Figure 9. Breaker in front of the dune without foreshore initial

Figure 10. Broken wave impinging on backrush water

Sediment Transport during the Development of Beach Profile

Notwithstanding already the difficulties which are connected to the calculation of sediment volume through one point of the beach during first increment of 80 waves this method was also applied for another 10 increments with a total of 760 waves. By this means the variation of sediment volume during the developing phase of the beach profile shall be demonstrated. Fig. 11 shows the comparison of both time-averaged results from the calculation and from the development of the beach profile. The measured and averaged value of sediment transport computed from profile changes over 760 waves yielded $\bar{A}$ = 1.07 m³/m ± 30 % (σ = 0.199) and $\bar{S}$ = 0.3 m³/m ± 30 % (σ = 0.063) for the calculated sediment transport. The difference between the averaged values is Δ = 0.77 m³/m or about 72 % (per increment = 70 waves).
The calculation with the average of instantaneous products of the sediment concentration and the water velocity

$$S = \int_0^t \int_0^z c(z,t) \cdot u(z,t) \, dz \, dt \tag{3}$$

is not possible, since the data of the sediment concentration are only time-averaged values.

It may be pointed out, that from the averages of instanntaneous products - obtained from 2-dimensional measuring systems - the sediment transport will not be described more accurately than the product of time-averaged sediment concentration and water velocity because measuring errors due to large vortex components have to be taken into account. In the present calculation these errors are compensated.

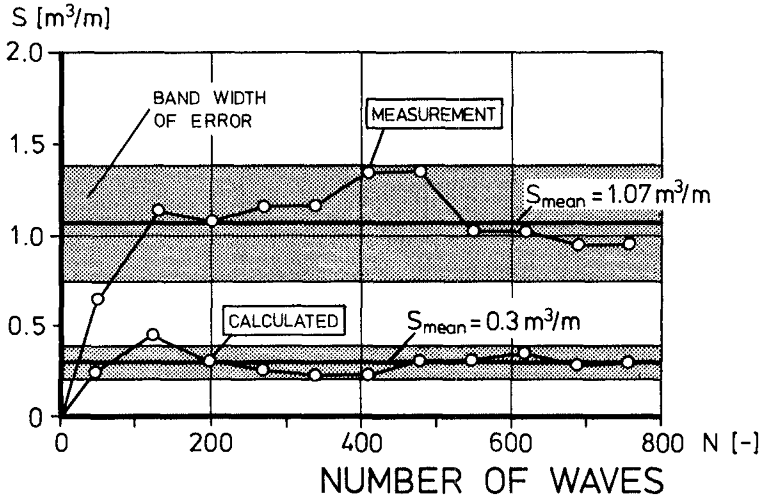


Figure 11. Comparison of sediment transport between the calculated transport and that computed from profile changes during development phase of beach profile (each value represents approx. a sequence of 70 waves)

Conclusion

The BIG WAVE FLUME in Hannover enabled prototype measurements of wave-induced velocities and sediment concentrations across the surf zone during the development phase of beach profile and over the equilibrium profile under regular and irregular waves.

In the paper first results of measurements obtained from two test series: "dune with and without foreshore" are presented.

At one position on the beach the calculated sediment transport was compared with the measured volume changes of the beach profile.

In order to minimize the differences between the calculated and measured values, it is necessary, to study in more detail the sediment transport in the bottom layer and to carry out measurements over the total column of water depth in the surf zone.

Acknowledgment

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List of Symbols

A	m^3/m	sedimentation
c	kg/m^3	sediment concentration
$\bar{c}$	kg/m^3	time-averaged sediment concentration
c_o	kg/m^3	calculated bottom concentration
D_{50}	μm	mean grain size diameter
$\bar{H}$	m	time-averaged wave height
H_o	m	deep water wave height
$H_{1/3}$	m	significant wave height
H_{rms}	m	root mean square wave height
L_o	m	deep water wave length
N	-	number of waves
S	m^3/m	total sediment transport
T	s	wave period
t	s	time
u	m/s	wave-induced current
$\bar{u}$	m/s	time-averaged wave-induced current
u_R	m/s	net wave-induced current
x	m	horizontal coordinate
z	m	vertical coordinate
σ	-	standart deviation
ξ_o	-	similarity index
σ_g	-	geometric standard deviation for grain size