CHAPTER 373

Cross-shore sediment transport mechanisms in the surfzone on a timescale of months to years

Klaas T. Houwman¹ and Gerben Ruessink¹

<u>Abstract</u>

The relevance of several cross-shore sediment transport mechanisms on a timescale of months to years was studied. Data from a large measuring campaign carried out in the outer surfzone of a barred surfzone was used to calculate sediment fluxes. The transport rates were calculated using the measured near bed velocities and sediment concentrations, and two sediment transport models. Both fluxes and the transport rates are only significant during breaking waves. The high-frequency fluxes/transports are onshore directed, the mean fluxes/transports are offshore directed, and the low frequency waves also give offshore directed fluxes/transports. Taking into account the frequency of occurrence of the conditions, the breaking wave conditions turned out to be the most important for the cross-shore sediment transport on a timescale of a year. The cross-shore sediment transport is a delicate balance between the onshore directed high frequency term and the offshore directed mean term. Therefore the smaller terms, like the low frequency term and the bedload term, may still be of importance to the net sediment transport.

Introduction

In the surfzone mean currents and high- and low frequency waves are responsible for sediment transport. Most field experiments presented in literature have focussed a typical time scale of a single storm-event. It is therefore unknown whether sediment transport on the scale of months to years is dominated by infrequent high energy conditions or by the often ocurring calm to moderate conditions.

In the frame work of the NOURTEC-project (Hoekstra et al., 1994) a shoreface nourishment was carried out in the multiple bar system of the Dutch island of Terschelling. A large-scale field measuring program, started to monitor this nourishment, offered an opportunity to determine the most important sediment

¹ Institute for Marine and Atmospheric Research, Utrecht University, Department of Physical Geography, P.O.Box 80.115, 3508 TC Utrecht, The Netherlands.

transport mechanisms at different locations in a barred surfzone and to evaluate the relevance of these mechanisms on a time scale of months to years. The sediment transport mechanisms were evaluated in the following way. Firstly, sediment fluxes were calculated using the measured velocity and sediment concentrations to determine the importance of mean currents, and high- and low-frequency waves to the *suspended* sediment transport on a time scale of a few weeks. These fluxes were related to the ratio of the local wave height and the local waterdepth (H_{m0}/h), incorporating both changes in wave conditions and tidal water levels. Secondly, the Bailard (1981)-approach was used to evaluate the relative importance of currents, high- and low frequency waves to the suspended sediment transport. The calculated contributions of the currents and waves were combined with a probability density function of H_{m0}/h to obtain insight in the effects on a timescale of years. Finally, a convection-diffusion sediment transport model (Van Rijn, 1993) was used, again in combination with probability density functions to evaluate the influence of waves and currents.

The Terschelling field site and data acquisition

The field experiment site is fully exposed to the North Sea with an annual mean significant offshore wave height of 1.1m (Van Beek, 1995). The tide is semidiurnal with a range of 1.5 and 2.5m during neap and spring tide, respectively. The nearshore area can be described as very dissipative with a very mild overall slope (1:200) and is characterized by the presence of several breaker bars (Hoekstra et al., 1994). In the period May 1994 to November 1995 three measuring campaigns were carried out: T2- (May and June 1994), T3- (October and November 1994), and the T4- (October and November 1995) campaign of five weeks each. The offshore significant wave height during the whole period ranged from 0.2 to 5m. During these campaigns four tripods (F2 to F5) were positioned in a cross-shore array (see Figure 1). Each tripod was equipped with two electro-magnetic flow meters (EMF) at an initial height of 0.25 and 1.2m above the bed and with a pressure sensor at 2.2m above the bed. On the tripods F3, F4 and F5 also two optical back scatter sensors (OBS) at 0.15m and 0.25m above the bed were installed. Timeseries were acquired with a sampling frequency of 2 Hz for 2048 seconds per hour. During the whole period from May 1994 to November 1995 the tripod F3 operated continuously (however without OBSs). At a waterdepth of 15m a wave directional buoy (WAVEC) was operational during the same period. The morphology landward of F4 evolved from a more or less alongshore uniform bar-trough system during the T2 and T3 campaigns to a three dimensional bar system during the T4 campaign. Seaward of F4 no large morphological changes were observed.



Figure 1. Instrumented positions and cross-shore profile of June 1994

Field observations of suspended sediment fluxes

Method

Fluxes were calculated from the measured timeseries of the cross-shore velocity u and concentration c. These timeseries were divided into a mean- and a high and low frequency oscillating term.

$$\langle u.c \rangle = \langle \overline{u}.\overline{c} \rangle + \langle \widetilde{u}_{\mu}.\widetilde{c}_{\mu} \rangle + \langle \widetilde{u}_{\mu}.\widetilde{c}_{\mu} \rangle$$
(1)

The left-hand side of (1) is the net suspended sediment flux; the first term on the right-hand side is the mean flux and the second and the third one are the high frequency and low frequency oscillating flux, respectively. The brackets denote time-averaged values. A positive flux is directed onshore. The separation frequency between high- and low-frequency waves was set to 0.04 Hz. Because of the different height at which u and c were measured, a correction for \bar{u} had to be applied. Here, a simple engineering rule was used (Van Rijn, 1991), which reads as

$$\bar{u}_1 = \bar{u}_2 \left(\frac{z_1}{z_2}\right)^{0.25}$$
 (2)

As a result, $\bar{\mathbf{u}}$ at z = 0.15 m was about 88% of that at z = 0.25 m. Very small offsets in \bar{c} (< 1 kgm⁻³) were encountered and corrected for. For this reason, the background concentration equaled 0 kgm⁻³.

Results

Burst-averaged values of the high- and low-frequency oscillating fluxes at z = 0.15 m at F3 (T2 and T4-), F4 (T2 +T3-) and F5 (T2 campaign) are plotted in Figure 2 as a function of the local relative wave height (spectral wave height based on short wave

band) H_{m0}/h . A study of Van Enckevort and Reincke (1996) made in the intertidal zone of the same cross-shore transect showed that initial wave breaking starts at $H_{m0}/h=0.33$. In other words, the highest wave in a wavegroup is breaking at this local relative wave height. Assuming that this relationship holds for the deeper parts of the nearshore zone, a distinction can be made between transport under breaking and nonbreaking wave conditions.

<u>F3</u>: At F3 non-zero fluxes only occured for H_{m0} /h values larger than about 0.3 - 0.35 at the lower sensor (Figure 2) and 0.35 - 0.4 at the upper one (not shown). In other words; when wave breaking occurs at that location. High-frequency fluxes were onshore directed and were associated with the horizontal asymmetry of the incident short waves, i.e. the difference in magnitude between onshore and offshore orbital motion. Low-frequency fluxes were rather small and seaward directed and were likely related to bound long waves.

For $H_{m0}/h < 0.3$ sediment was not resuspended on the time scale of individual short waves nor on that of wave groups. The negligible oscillating fluxes for $H_{m0}/h < 0.3$ thus seemed to be mainly due to a lack of coherence between u and c for almost all frequencies. In addition, the variance in c was very low at both sensors compared to more energetic events.

For $H_{m0}/h > 0.3$ sediment was stirred on both the individual short-wave and wavegroup time scale. The co-spectrum between *u* and *c* showed the 'classic' shape of a large positive (onshore) peak at the peak frequency of the short waves and a broad negative (offshore) peak at infragravity frequencies (cf. Huntley and Hanes, 1987). The phases at the peak frequency were between -45 and 0 degrees, which indicates that *c* lagged *u* slightly. Phase lags between both sensors were, in general, negligible at both high and low frequencies.

The oscillating fluxes at z = 0.25 m were considerably smaller than at z = 0.15 m. The sediment fluxes at the upper OBS were about 29 % and 4 % of that at the lower OBS for the high- and low-frequency sediment flux, respectively.

Time-averaged values of the mean flux at z = 0.15 m are also shown in Figure 2 as a function of H_{m0}/h . The largest fluxes, which were in a seaward direction, occured for conditions with H_{m0}/h above 0.3 to 0.35. This indicates that these negative fluxes were associated with wave-driven undertows.

<u>F4:</u> The same pattern for the oscillating fluxes and the mean fluxes were also found at F4. However, during one wave event offshore directed high frequency fluxes occured as well, caused by phase lags between \tilde{u}_h and \tilde{c}_h larger than 90 degrees. The reason for these large phase lags is not fully understood. In general, phase lags are ascribed to the presence of ripples (e.g., Vincent and Green, 1990), though they have also been observed in the sheetflow regime (e.g., Ribberink and Al-Salem, 1995). Why such large phase lags developed during this particular storm (presumably sheet flow conditions) and not during other ones or at other positions is unknown. The mean fluxes at F4 were not only offshore directed due to undertows, but also onshore directed velocities and fluxes were observed (Figure 2). The origin of these onshore currents is not clear. On average, the mean fluxes were offshore directed and the averaged high-frequency fluxes onshore.

<u>F5</u>: In the trough at F5, no breaking wave conditions occured ($H_{m0}/h < 0.3$). Although some scatter is present at the high frequency fluxes (Figure 2), no systematic contribution of this term was found. The scatter at the mean fluxes was not the result of enhanced cross-shore currents, but was caused by high sediment concentrations unrelated to the cross-shore velocity signal. These high sediment concentrations were probably the result of the tidal longshore currents in combination with bedforms.



Figure 2. Measured fluxes at 15 cm above the bed at F3, F4 and F5

Long-term suspended sediment transport: an energetics approach

Introduction

The analysis of the suspended sediment fluxes at a height z above the bed has given important insight into the magnitude, direction and relative importance of different processes to the total suspended sediment transport. However, the findings strictly apply to the height z and are, therefore, not necessarily representative for the depthaveraged fluxes. Furthermore, the analysis presented sofar has not taken the longterm distribution of the hydrodynamical conditions into account. The magnitude of the fluxes increased with H_{m0}/h , but this does not necessarily mean that on a time scale of months to years the sediment transport is limited to conditions which occurrence in time is only infrequent. The cumulative effect of small, but often occurring transports may outweigh that of large, but rarely present ones. The crossshore transport rate under mean and oscillating flows can relatively simple be modelled with a formulation in which the sediment transport rate is assumed to respond instantaneously to fluctuations in velocity above the bed (Bowen, 1980; Bailard, 1981). This rate is then expressed as a linear combination of terms containing products of the three different velocity components \tilde{u} , \tilde{u}_h and \tilde{u}_l . These terms, referred to as 'velocity moments', represent the depth-averaged sediment fluxes.

Roelvink and Stive (1989) showed that the most important contributions to the magnitude and the direction of suspended load transport is given by the term $\langle |u(t)|^3 u(t) \rangle$. This term can be expanded in several terms after replacing the instantanous velocity u(t) by a sum of the mean, high and the low frequency oscillating velocity. The most important terms (Roelvink and Stive, 1989) are:

$$<|u|^{3}u> = 4<|\tilde{u}_{h}|^{3}\bar{u}> + <|\tilde{u}_{h}|^{3}\tilde{u}_{h}> + 4<|\tilde{u}_{h}|^{3}\tilde{u}_{l}>$$
 (3)

In these terms the stirring of sand is proportional to $|\tilde{u}_h|^3$. The sediment is then transported by any mean current, by high-frequency (HF) and low-frequency (LF) oscillations. Under breaking wave conditions in shallow water other velocity moments, such as those related to the stirring of sediment by long waves ($|\tilde{u}_l|^3$), may become of importance as well (Foote et al., 1994; Kroon, 1994), but these terms are neglected in the present analysis. The velocity moments were scaled with the inverse of the fall velocity *w* to investigate their cross-shore variability. The drag - and the efficiency coefficient (Roelvink and Stive, 1989) were assumed to be constant over the profile. The median sediment fall velocity at F2, F3, F4 and F5 were 15.1, 17.7, 27.6 and 20.5 mm/s, respectively (Guillén and Hoekstra, 1996). The velocities of the lower EMF were used to calculate the velocity moments. It should be emphasized that the energetics approach is only applied to investigate trends; quantitative information on the time-averaged transport rates is not a subject of this section.

Results

The w⁻¹-scaled velocity moments are shown in Figure 3 as a function of H_{m0}/h . The lines shown in Figure 3 are based on the average values of a particular H_{m0}/h -class (width =0.02). At each position the w⁻¹-scaled velocity moments were clearly related to H_{m0}/h , and the growth of the velocity moments start at $H_{m0}/h=0.3$. In general, the contribution of $\langle |\tilde{u}_{h}|^{3}\tilde{u}_{h} \rangle$ (HF) and $\langle |\tilde{u}_{h}|^{3}\tilde{u} \rangle$ (mean) to the total fourth-order velocity moment were about equal, but of opposite sign. Consequently, the LF-term $\langle |\tilde{u}_{h}|^{3}\tilde{u} \rangle$, which had a negative sign and was smaller than both $\langle |\tilde{u}_{h}|^{3}\tilde{u}_{h} \rangle$ and $\langle |\tilde{u}_{h}|^{3}\tilde{u} \rangle$, often strongly influenced the size and the direction of the net fourth-order velocity moment. The fourth-order velocity moments at F5 were minimal compared to those at the other postions indicating negligible suspended sediment transport in the middle trough.



Figure 3. Measured scaled velocity moments and probability density function of (Hm0/h)



Figure 4. Long term transport rates weighted for the frequency of occurrence

An impression of the long-term effect, i.e. on the time scale of months to a few years, can be obtained by multiplying the H_{m0} /h-dependence of the velocity moments with the probability density function of H_{m0} /h at that location. At each location the frequency of occurence of H_{m0} /h is known from the measurements. Figure 3 also shows the probability density function (pdf) of H_{m0} /h ($p(H_{m0}/h)$) at each position. The pdf of F2, F3, F4 and F5 are determined based on measured data of 2682, 9220, 1551 and 1541 hours, respectively.

The product of the pdf and the w^{-1} -scaled velocity moments is shown in Figure 4. Significant contributions of the separate processes to the long-term suspended sediment transport started from a value of $H_{m0}/h = 0.25$ at F2, and of $H_{m0}/h = 0.15$ at F3 and F4, which means that the suspended sediment transport was restricted to 3.4%, 32% and 51% in time at F2, F3 and F4, respectively. The majority of the suspended sediment transport (about 70 to 90 %) took place, however, when wave breaking occurred at that location ($H_{m0}/h > 0.33$) and as a consequence, was limited to a much smaller amount in time (1.8, 5.6 and 8.5% in time respectively). This does not imply that the long-term suspended sediment transport is restricted to truely

extreme events, except perhaps at F2. For decreasing water depths the occurence of the long-term suspended sediment transport shifts towards more common conditions, although it remains largely restricted to conditions with breaking waves.

The products of the pdf and the velocity moments are in the same order at F2, F3 and F4 and much smaller at F5. The approximately equal net long-term suspended sediment transports at F2, F3 and F4 are caused by the fact that the two largest contributions, viz. the high-frequency oscillating and current-related one, are nearly the same and, therefore, cancel out. This implies that the cross-shore suspended sediment transport is a delicate balance between contributions by mean currents, and by high- and low-frequency waves. The present results have also indicated that the long-term suspended sediment transport in the middle trough is very small.

Long-term sediment transport: the Van Rijn/Ribberink model

Method

The Van Rijn/Ribberink model (Van Rijn, 1993) was used to calculate the sediment transport. This model is a combination of two different submodels: a suspended load (Van Rijn, a convection-diffusion model) and a bedload one (Ribberink). In the suspended load model the stirring of the sediment is the result of both waves and currents. However, the suspended sediment is only transported by mean currents; oscillating suspended load transport is not included. The bedload model, however, is an instantaneous model. As a result, the sediment can be transported due to both waves (short and long waves) and currents. The model has been modified in such a way that timeseries of measured velocities and waterlevels can be used as input instead of the vertical mean velocity and wave height (Houwman and Hoekstra, 1994). Timeseries of the T2- and T4-campaigns at position F2, F3, F4 and F5 were

used to calculate the sediment transport. The measured timeseries of velocities u and v (at 0.25 m above the bed) and the measured waterlevels (measured by the pressure sensor at 2.2 m above bed) were used as input into the model. From these velocity signals the near bed velocity distribution was constructed assuming a logarithmic velocity profile for the mean current and a constant orbital velocity distribution in the vertical. Only measured velocity signals were used, therefore the effect of the wave induced near bed velocity ('Longuet-Higgins streaming') was not included in the computations. For the computations the local median grain size was used (d₅₀ is 154, 163, 172 and 178 μ m for F2, F3, F4 and F5 respectively) and a constant bed roughness height k_s = 0.3 cm.

The previous analysis of the fluxes and the velocity moments showed that the highfrequency suspended load transport cannot be neglected. To get insight in contribution of this term to the net transport, the Van Rijn model is modified in the following way. The model produces a time-averaged sediment concentration distribution over the vertical. At a certain height above the bed this mean sediment concentration is thought to be the time averaged value of two sediment concentration peaks per wave cycle, one during the onshore directed wave motion and the other during the offshore directed peak. According to the velocity moments approach the shape of the sediment concentration peaks can be assumed to be equal to the shape of $|u(t)|^3$. If one also assumes that each half wave cycle can be described with linear wave theory with different amplitudes but with equal duration, equation (4) is derived.

$$\overline{c}(z) = k \left[\left| \frac{2}{T} \int_{0}^{T/2} U_{on}^{3} \sin^{3} \omega t \, dt \right| + \left| \frac{2}{T} \int_{T/2}^{T} U_{off}^{3} \sin^{3} \omega t \, dt \right| \right]$$

$$= k * [U_{on}^{3} + U_{off}^{3}] * \left| \frac{2}{T} \int_{0}^{T/2} \sin^{3} \omega t \, dt \right|$$
(4)

In equation (4), the left term is the time averaged sediment concentration at height z above the bed, U_{on} and U_{off} refer to the onshore and offshore peak orbital velocity, T and $\boldsymbol{\omega}$ are the wave period and angular frequency, respectively and k is a constant. The oscillating suspended flux at a certain height z above the bed can be related to the fourth order moment $u^*|u^3|$. The wave averaged oscillating sediment transport rate S(z) through a layer dz is then described by (5):

$$S(z) = \frac{1}{T} \int_{0}^{T} k * u(t) |u(t)^{3}| dt dz = k [U_{on}^{4} - U_{off}^{4}] dz * \frac{1}{T} \int_{0}^{T} \sin^{4} \omega t dt$$
(5)

$$S(z) = k' * \bar{c}(z) * \frac{U_{on}^4 - U_{off}^4}{U_{on}^3 + U_{off}^3} * dz$$

with :
$$k' = \frac{1}{2} \int_{0}^{T} \sin^4 \omega t \, dt * \left[\int_{0}^{T/2} \sin^3 \omega t \, dt \right]^{-1} \approx 0.884$$

After integration over the vertical the oscillating suspended sediment transport can be obtained. The mean concentration at height z above the bed is calculated with the Van Rijn/Ribberink model, and the measured significant onshore and offshore orbital motions can be used.

This approach gives an upper limit for the suspended oscillating sediment transport, because one assumes that there are no phase lags present between u(t) and c(t) and that the sediment always responds instantaneously to the third power of the orbital velocity. However, the measurements have shown that phase lags were present and it is unclear if the sediment always responded to $u(t)^3$. Therefore, the parameter k' in (5) is replaced by a new parameter, the "efficiency coefficient" (*eff*) which incorporates these effects. This parameter was determined from the OBS data.

The measured fluxes were divided by the mean concentration for both OBSs at F3 and were related to the significant orbital velocity. The relative (to the mean) response of the sediment is important, because the mean concentration c(z) is obtained from the model. The values are averaged for an orbital velocity class (width of 0.1m/s), based on data of the T2, T3 and T4 campaigns. A comparison between the measured values and the values of the fourth-order moment show that no fixed k' values can be taken. Based on the two lines from both OBSs the efficiency coefficient was determined as:

$$eff(U_{on}, z) = [(2.5 * z - 0.292) * U_{on} - 3 * z + 0.42] * \tanh(6.5(z_{max} - z))$$

$$IF \ eff(U_{on}, z) < 0 \ \neg \ eff(U_{on}, z) = 0$$
(6)

To prevent that large oscillating fluxes are calculated far away from the bottom, a tanh function was used to force the efficiency coefficient down to zero again at a particular height (z_{max}) above the bed. The model outcomes were not very sensitive for the values of z_{max} . In the calculations a value of 0.6 m was chosen fo_{max} . A comparison between the 'theoretical' efficiency coefficient k' and the 'observed' efficiency coefficient makes clear that the theoretical one is significantly higher than the observed one. At a height of 0.25 m above the bed the observed efficiency coefficient ranges from 0 to 0.2 (at $U_{on} = 1.6$ m/s) instead of having a fixed value of

0.884. The oscillating suspended load sediment transport was also calculated at F4 using the same formulation for the efficiency coefficient. The observed values were described reasonably by the model. Therefore the approach described above was used for all tripods.

Results

From the calculated cross-shore transport rates an average sediment transport can be calculated for a particular relative wave height class (H_{m0}/h) . Figure 5 shows the transport rates calculated at four locations and split up into the contribution of the three transport mechanisms: bed(load), mean- and osc(illating suspended load) transport. The $p(H_{m0}/h)$ for each position are also given. At F2, F3 and F4 the mean and oscillating suspended load transport increased rapidly for situations with a relative wave height larger than 0.3.

The 'yearly-averaged' transport rates shown in Figure 6 were created in a similar way with the pdfs as for the velocity moments. For both F2 and F3 the oscillating and mean suspended load sediment transport were very high during breaking wave conditions ($H_{m0}/h > 0.33$). The yearly net sediment transport is a sensitive balance between the offshore directed mean suspended load transport and the onshore directed oscillating suspended load transport, the contribution of the bedload transport at these positions is only small. However, the difference between the relative large contributions of the suspended load transport on the net transport is not clear yet. Again at location F4 the mean suspended load is neutralized by the oscillating suspended load component. The magnitudes of the different yearly averaged transport rates at F2, F3 and F4 were of the same order of magnitude.

In the trough at the position F5 the cross-shore sediment transport rates were much lower and offshore directed. The lack of any onshore transport mechanism in the trough region indicates that no large onshore exchange of sediment across the trough may be expected.

Discussion and conclusions

The field measurements at Terschelling have shown that high- and low-frequency waves, as well as mean currents, contribute to the net suspended sediment transport. In general, the high-frequency oscillating transport is onshore directed and is caused by the positive skewness of the short waves. The low-frequency oscillating transport is in a seaward direction owing to the dominance of bound long waves in the total long wave field and the stirring of sediment on the wave-group time scale. The current-related flux is in an offshore direction in most cases and is caused by wavedriven undertows.

The "measured" fluxes start to increase at a relative wave height $H_{m0}/h > 0.33$, which coincides with breaking wave conditions. The velocity moments are increasing at a lower H_{m0}/h ratio (0.15 - 0.25) but also here the highest transport rates were found during breaking wave conditions. The suspended load transport rates calculated with



Figure 6. Long term transport rates weighted for the frequency of occurrence

the Van Rijn model were only non-zero during these conditions ($H_{m0}/h > 0.33$) as well. In general, the suspended load transport rates are well related to the relative wave heights H_{m0}/h .

All three applied methods show that the contributions of the onshore directed oscillating suspended load transport or flux is more or less balanced by the offshore directed mean transport/flux.

The combination of a local probability density function (pdf) and the calculated velocity moments and transport rates gives insight in the long term contributions of different transport mechanisms. The yearly averaged suspended load transport rates obtained in this way, start to increase at $H_{m0}/h>0.33$ for F2, F3 and F4. This indicates that on the long run only breaking wave conditions are important at these positions. But again, at this time scale the suspended sediment transport is a delicate balance between the onshore directed (short wave) oscillating transport and the offshore directed mean transport.

The contribution of the low frequency suspended load transport is rather small compared to the high frequency and mean transport but is systematic and therefore still significant. The calculations of the bedload transport have shown that this contribution is very small compared to the other terms. Although the contributions of the low frequency suspended transport and the bedload transport are small their importance will increase when the mean suspended transport is neutralized by the oscillating high frequency transport.

The results obtained from the calculated long term transport rates are not in agreement with the beach-shoreface exchange mechanism proposed by Niederoda et al. (1984). They found an offshore directed sediment transport from the beach/inner surfzone to the upper shoreface (h > 4m) during a storm and a slow return of this sediment during low energetic conditions in response of asymmetric waves propagating to the coast. If this mechanism is also valid for the Terschelling coast one expects a large contribution of the short wave transport during non-breaking wave conditions. However, for the whole range of H_{m0}/h values the terms are in balance and no clear dominance of a term at a particular H_{m0}/h value has been found. In addition, the morphological observations do not support the theory of such a systematic exchange mechanism between beach and deeper water.

The lack of significant sediment transport in the trough at location F5 also prevents a large exchange between the shallow water and deep water region. In the trough no waves break, and the calculated transport rates are very low. It seems that the landward-located trough acts as a barrier against cross-shore sediment transport.

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