LONGSHORE SAND TRANSPORT

Leo C. van Rijn[1]

Abstract: Various reliable data sets from sites (USA and Netherlands) have been selected to analyse the longshore transport process and to establish the relationship between wave height, wave incidence angle and longshore transport, yielding a relatively simple transport formula. The data set was too small to detect any influence of particle size, wave period and profile shape. These aspects were studied by using the results of a detailed process-based model, which were parameterized and implemented in the simplified formula. The main overall result is a general expression for longshore transport of sand and gravel, including the effects of profile slope and tidal velocity.

INTRODUCTION

The computation of a reliable estimate of longshore sand transport remains of considerable practical importance in coastal engineering applications such as the derivation of sediment budgets for coastal areas with and without structures (breakwaters, groynes) and long-term beach stability with and without beach nourishments or coarse-grained beach protections. Most research on longshore transport has concentrated on sand sized sediment, but research on longshore transport along gravel and shingle beaches has also been performed to deal with the erosion problems along these types of beaches, which are quite common along mid- and high-latitude (formerly glaciated) parts of the world.

The most widely used formula for longshore transport (LST) is commonly known as the CERC equation (Shore Protection Manual, US Army Corps of Engineers, 1984). This method is based on the principle that the longshore transport rate (LST, incl. bed load and suspended load) is proportional to longshore wave power P per unit length of beach; LST=K P, with K=calibration coeffcient. The CERC formula has been calibrated using field data from sand beaches. The effects of particle diameter and bed slope have been studied systematically by Kamphuis (1991), resulting in a more refined equation for longshore sediment transport. This latter equation was found to give the best agreement between computed and measured transport rates (Schoonees and Theron, 1996). Both equations (CERC and KAMPHUIS) have been used in the present study. Furthermore, a detailed process-based model (CROSMOR2000) has been used in this study to compute the longshore sand transport distribution along the cross-shore bed profile. First, this model

1 Senior engineer, Delft Hydraulics, PO Box 177, 2600 MH Delft, Netherlands; leo.vanrijn@wldelft.nl.

was tested using the available field data sets. Then, the model was applied to study the systematic effects of particle size, wave period and profile shape on the longshore transport process.
Schoonees and Theron (1993) have made an extensive inventory of the available data sets of longshore sand transport rates, resulting in 273 data sets for bulk transport rates from a variety of sites around the world. Most data sets refer to mild wave conditions with offshore wave heights smaller than about 2 m and bed material in the sand range of 0.2 to 0.6 mm. Hence, most existing formulae have been calibrated for mild wave conditions and not for storm conditions, because of lack of data. The lack of data in the storm range was partly solved by the special storm measurements performed by the US Army Corps of Engineers (USACE) from the Field Research Facility at the Duck site (USA) in the years of 1995 to 1998 (amount of field data sets is still extremely small). These latter data sets with longshore transport rates in conditions with offshore wave heights up to 4 m have also been used in this study. The USACE (H. Miller) is gratefully acknowledged for providing these data sets.
In all, seven reliable data sets from various sites in the USA and in The Netherlands have been selected from the available data bases to analyse the longshore transport process in the present study. This relatively small high-quality data set was used to establish the relationship between wave height, wave incidence angle and longshore transport, yielding a relatively simple transport formula. The data set was too small to detect any influence of particle size, wave period and profile shape. These aspects were studied by using the results of the detailed CROSMOR2000 model, which were parameterized and implemented in the simplified formula. The main overall result of the present study is a general expression (similar to the CERC/KAMPHUIS formulae) for longshore transport of sand and gravel/shingle, including the effects of profile slope and tidal velocity. The coefficients and factors of the new formula are based on computational results of the detailed CROSMOR2000 model.

DESCRIPTION OF MODELS

The following formulations have been used in the present study (see also Van Rijn, 1993):

- CERC formula,
- KAMPHUIS 1991 formula,
- CROSMOR2000 model (proces-based numerical model).

CERC formula

The CERC-formula developed by the US-Corps of Engineers relates the immersed weight (I) of the longshore sediment transport rate to the longshore wave energy flux factor (Shore Protection Manual, 1984):

$$I = K\, E\, c_{g,br} \sin\theta_{br} \cos\theta_{br} \qquad (1)$$

in which: I =longshore transport rate (immersed weight); E =1/8 $\rho g (H_{rms,br})^2$ = wave energy at breaker line; $H_{rms,br}$ =rms wave height at breaker line; $c_{g,br}$ =$n_{br}\, c_{br}$ = wave group celerity at breaker line; θ_{br} =wave angle at breaker line (between wave crest line and coastline; or between wave propagation direction and shore normal direction); K = coefficient (= 0.77).

Early calibration of the CERC-formula was based upon 9 field data points and 150 laboratory data points resulting in K = 0.42. Subsequent calibration based on the original 9 field data points plus 14 additional field data points with all laboratory data deleted resulted in K = 0.77, which is the recommended value to date for use with $H_{rms,br}$ (Shore Protection Manual, 1977, 1984). Since then, more field data points have become available. The K-values reported for these studies range from 0.2 to 1.6 (Bodge and Kraus, 1991).

Using the significant wave height ($H_s = \sqrt{2}\, H_{rms}$), ρ= 1030 kg/m^3, K=0.77 and p= 0.4, Equation (1) can be rearranged to:

$$Q_{t,vol}=0.023\, (H_{s,br})^2\, n_{br}\, c_{br}\, \sin(2\theta_{br}) \qquad (2)$$

in which: $Q_{t,vol} = I/((1-p)(\rho_s-\rho)g)$ = longshore sediment transport by volume (m^3/s, including pores); the sediment transport by dry mass is $Q_{t,mass}=(1-p)\, \rho_s Q_{t,vol}$; $H_{s,br}$=significant wave height at the breaker line (m); c_{br} =phase velocity of the waves at the breaker line ≅ $(g\, h_{br})^{0.5}$; n_{br} =coefficient at breaker line ≅ 1; θ_{br}=wave angle at the breaker line (°); h_{br}=water depth at the breaker line (m); p=porosity factor (≅ 0.4); ρ_s=sediment density (≅ 2650 kg/m^3).

Applying n_{br} ≅ 1, c_{br} ≅ $(g\, h_{br})^{0.5}$, and $\gamma_{br} = H_{br}/h_{br}$, Equation (2) can be rearranged to:

$$Q_{t,vol} = 0.023\, g^{0.5}\, (\gamma_{br})^{-0.51}\, (H_{s,br})^{2.5}\, \sin(2\theta_{br}) \qquad (3)$$
$$Q_{t,mass} = 0.023\, (1-p)\, \rho_s\, g^{0.5}\, (\gamma_{br})^{-0.52}\, (H_{s,br})^{2.5}\, \sin(2\theta_{br}) \qquad (4)$$

Using p= 0.4, ρ_s = 2650 kg/m^3 and γ_{br}= 0.8, this yields:

$$Q_{t,mass} = 128\, (H_{s,br})^{2.5}\, \sin(2\theta_{br}) \qquad (5)$$

The most important parameters are the wave height and the wave angle. An error of 10% in the wave height at the breaker line yields a 25% error in the transport rate. According to Eq. (5), the transport is linear with θ_{br} for small angles. Equation (5) is a rather crude formula, not showing any influence of the particle diameter and the beach slope inside the surf-zone. Therefore, the CERC-formula is only valid for a narrow range of conditions as represented by the calibration data. According to Kamphuis (1991), the standard CERC-formula (K=0.77) considerably overpredicts measured transport rates for particle sizes in the range of 0.2 to 0.6 mm 3 and beach slopes in the range tanβ4 = 0.01 to 0.1. The CERC-formula cannot be applied when tidal current velocities are significant.

KAMPHUIS 1991 formula

Based on dimensional analysis and calibration using laboratory and field data, the longshore transport as immersed mass (in kg/s) is given by:

$$Q_{t,im}=2.33\, (T_p)^{1.5}\, (\tan\beta)^{0.75}\, (d_{50})^{-0.25}\, (H_{s,br})^2\, [\sin(2\theta_{br})]^{0.6} \qquad (6)$$

with: $Q_{t,im}$=longshore sediment (immersed mass) transport (kg/s); the dry mass is related to the immersed mass by $Q_{t,mass}=\rho_s/(\rho_s-\rho)\, Q_{t,immersed\ mass}$; the conversion factor is about 1.64;
$H_{s,br}$= significant wave height at breaker line (m); θ_{br} =wave angle at breaker line (°);
d_{50} =median particle size in surfzone (m); tanβ=beach slope defined as the ratio of the water depth at the breaker line and the distance from the still water beach line to the breaker line;
T_p = peak wave period.
The value 2.33 is a dimensional coefficient related to the SI system assuming salt water (1030 kg/m^3).

CROSMOR2000 model

A detailed surf zone model (CROSMOR2000) has been used to compute the cross-shore distribution of wave height, longshore velocity and longshore sand transport (bed load and suspended load transport), (Van Rijn, 2000). The CROSMOR 2000 model comprises three submodules: hydrodynamics (waves, currents), sand transport and bed level evolution (morphology). The sand transport module is based on the TRANSPOR2000 model (Van Rijn, 2000).

The CROSMOR2000 model is being used here as a representative model from the class of process-based cross-shore models. The CROSMOR2000 model performed reasonably well within the COAST3D model evaluation study (Van Rijn, 2001; Van Rijn et al., 2002, 2003). The probabilistic CROSMOR2000 model is used herein, because the longshore current velocity is reasonably well simulated due to the representation of the full wave spectrum (wave classes) resulting in more realistic wave breaking (differential breaking: larger waves break at other locations than smaller waves) than based on the Battjes-Janssen approach (1978) used by the deterministic models. Furthermore, the lateral (cross-shore) mixing effect is taken into account.

In the CROSMOR 2000 model, the propagation and transformation of individual waves (wave by wave approach) is described by a probabilistic model (Van Rijn and Wijnberg, 1994, 1996) solving the wave energy equation for each individual wave. The individual waves shoal until an empirical criterion for breaking is satisfied. Wave height decay after breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore currents including cross-shore mixing effects are also modelled. Wind-induced and tide-induced effects on the longshore current are taken into account. The standard wave breaking coefficient is represented as a function of local wave steepness and bottom slope. Laboratory and field data have been used to calibrate and to verify the model. Generally, the measured $H_{1/3}$-wave heights are reasonably well represented by the model in all zones from deep water to the shallow surf zone, as shown within the COAST3D verification study (Van Rijn et al. 2002, 2003) and other studies (Grasmeijer et al., 2000).

The depth-averaged longshore current is computed from the depth-averaged momentum equation for the longshore direction including wind-induced, tide-induced and radiation stress terms. The longshore water surface gradient is computed from a given (measured) depth-averaged longshore velocity (input data; usually tidal velocity) at the offshore boundary and is assumed to be constant in cross-shore direction. The term representing the cross-shore exchange of momentum is modelled as a dispersion term.

ANALYSIS OF MEASURED LONGSHORE TRANSPORT RATES

In the present study the attention is focussed on data sets based on short-term measurements using direct sampling methods or short-term volume changes (<1 day; Indian Rocks beach, USA). As regards long-term volume changes, only one case with a predominant wave direction has been considered (Leadbetter Beach, USA). The basic data sets and the detailed selection aspects of these field cases are discussed by Van Rijn (2001). Based on the evaluation of older data sets and more recent data sets, the following (reasonably reliable) data sets have been selected for testing of longshore sand transport models, being:

- **South Lake Worth, Florida, USA (1953)**; low wave and microtidal conditions (swell); medium coarse sand bed of 0.4 to 0.6 mm; data based on bypassing rate of sand pumping plant;

- **Leadbetter Beach, California, USA (1981)**; low and mild wave conditions (swell); fine sand of 0.2 to 0.25 mm; data based on morphological volume changes along beach over about 1 year;
- **Lake Michigan, Wisconsin, USA (1975)**; low wave energy conditions; medium fine sand of 0.2 to 0.3 mm; data based on trap samplers;
- **Price Inlet, South Carolina, USA (1977)**; low wave energy conditions (swell); medium fine sand of 0.2 to 0.25 mm; data based on trap samplers;
- **Indian Rocks beach, Florida, USA (1999)**; low wave-energy and microtidal conditions; medium coarse sand bed of 0.35 mm; data based on short-term morphological volume changes (<1 day);
- **Duck site, USA (1985 and 1995-1998)**; fine sand bed of 0.15 to 0.2 mm;
  - swell conditions during survey in September 1985 (Kraus and Dean, 1987); data based on sampling using streamer traps;
  - minor to major storm and microtidal conditions, (Miller, 1999); data based on concentration sampling method.

The measured total longshore sand transport rates are plotted in Figure 1 as function of the parameter W= $(H_{s,br})^3 \sin(2\theta_{br})$. Several other values (between 2 and 4) of the exponent were also used, but a value of 3 produced the best results. Most transport rates are within a factor 2 of the plotted trend line.
The trend line can be represented by:

$$Q_{t,mass}=40\ (H_{s,br})^3 \sin(2\theta_{br}) \qquad (7)$$

with: $Q_{t,mass}$ = longshore sand transport (in kg/s; dry mass); $H_{s,br}$ = significant wave height at breakerline (in m); θ_{br} = wave incidence angle (to shore normal) at breakerline (degrees).
Equation (7) is valid for sand in the range of 0.15 to 0.5 mm and beach slopes in the range of 0.02 to 0.1. The measured longshore transport rates at Leadbetter Beach may overestimate the transport in the surf zone, because the measured values include the zone seaward of the surf zone (soundings down to the 10 m depth contour). The complete data set is too small to detect any influence of particle size and or beach slope.

Using an approach similar to that of Bagnold (1963) and Komar (1979), Equation (7) can also be expressed as:

$$Q_{t,mass}= K_1\ (H_{s,br})^{2.5}\ V_{wave,L} \qquad (8)$$

$$V_{wave,L}=K_2\ (gH_{s,br})^{0.5} \sin(2\theta_{br}) \qquad (9)$$

with: $V_{wave,L}$= longshore current velocity in mid of surf zone due to breaking waves;
$K_1 K_2 g^{0.5}$ = 40 and K_2= 0.3.
The longshore transport rate is described as a combination of a wave-related stirring parameter and a wave-driven longshore current velocity ($V_{wave,L}$) in the middle of the surf zone. The K_2 coefficient is about 0.3 based on analysis of measured longshore current velocities at the Duck site (USA) and at the Egmond site (Netherlands), as shown in Table

1 (Van Rijn, 2001). Equations (8 and 9) will be used later to include the tide-driven longshore velocity.

Site	Wave incidence angle at breakerline θ_{br} (^{o})	Significant wave height at breakerline $H_{s,br}$ (m)	Measured longshore velocity V_L (m/s)	Computed longshore velocity V_L (m/s)
Egmond	**1998**			
B 9416	15-20	2.5-3.0	0.6-0.8	0.7-1.1
B9424	3-5	3.0-3.5	0.3-0.5	0.2-0.3
B9402	20-25	3.0-3.5	1.0-1.4	1.1-1.3
B9412	25-30	3.0-3.5	1.0-1.4	1.3-1.5
Duck 1995-	**1998**			
14 November	10-15	1.5-2.0	0.2-0.5	0.3-0.6
11 March	10-15	2.0-2.5	0.4-0.8	0.4-0.6
27 March	15-20	1.5-2.0	0.3-0.6	0.6-0.8
2 April	15-20	1.5-2.0	0.3-0.6	0.6-0.8
1 April	15-20	2.5-3.0	0.9-1.5	0.6-0.9
19 october	15-20	3.0-3.5	1.0-1.6	0.8-1.1
4 February	15-20	3.0-3.5	1.0-1.4	0.8-1.1

Table 1 Measured and computed longshore velocities at Egmond and Duck site

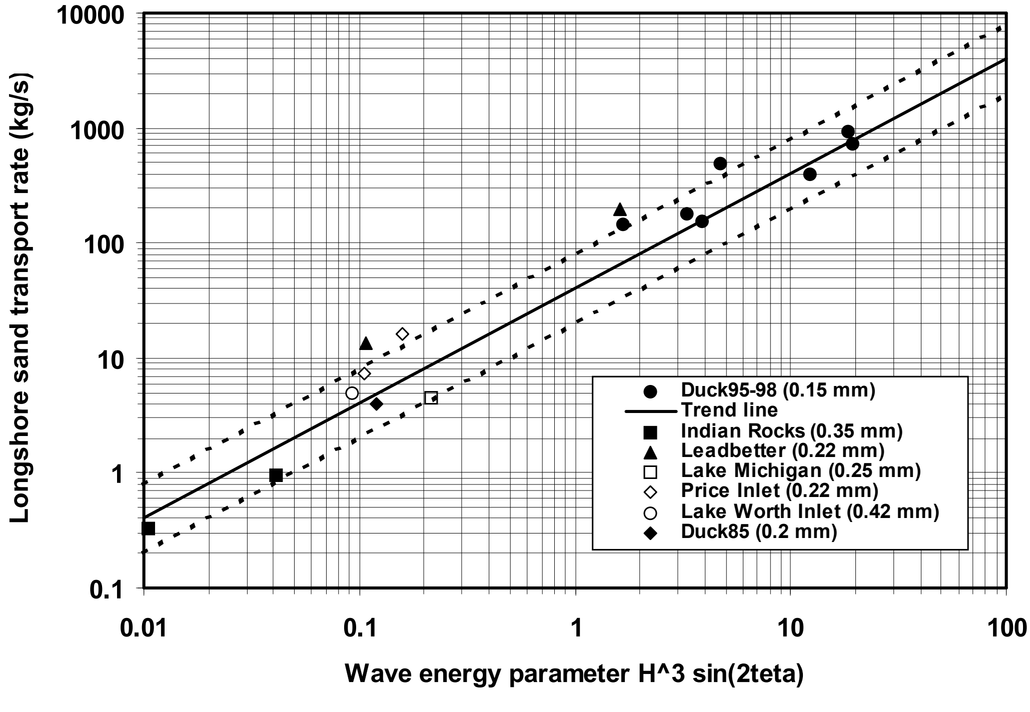

Figure 1 Longshore sand transport as function of wave energy parameter

The available data sets have also been used to test the three prediction methods. The results are given in Figure 2. Based on this, the following conclusions can be given:

- the CERC formula yields results, which are slightly too large (factor 2) compared with measured values for storm conditions (high energy events), but much too large (factor 5) for low wave conditions;
- the KAMPHUIS formula yields results, which are slightly too small (factor 1.5) compared with measured values for storm conditions (high energy events) but much too large (factor 3) for low wave conditions; this behaviour is caused by the second power relationship between transport and wave height (field data show the presence of a third power relationship);
- the CROSMOR2000 model yields results, which are slightly too large (factor 1.5) compared with measured values for storm conditions (high energy events) and somewhat too small (factor 2) for low wave conditions; a quasi-regular wave approach yields the best results for swell-type wave conditions; the underprediction for low wave conditions may be related to the exclusion of the longshore transport in the swash zone, which is relatively important for low wave conditions;
- the CROSMOR model yields reasonable results for a wave-related ($k_{s,w}$) bed roughness of about 0.03 m for all Cases considered; the current-related ($k_{s,c}$) bed roughness was found to be in the range of 0.01 m for low wave conditions (2D wave ripples in cross-shore direction) to 0.03 m for storm conditions (3D mega ripples in longshore direction).

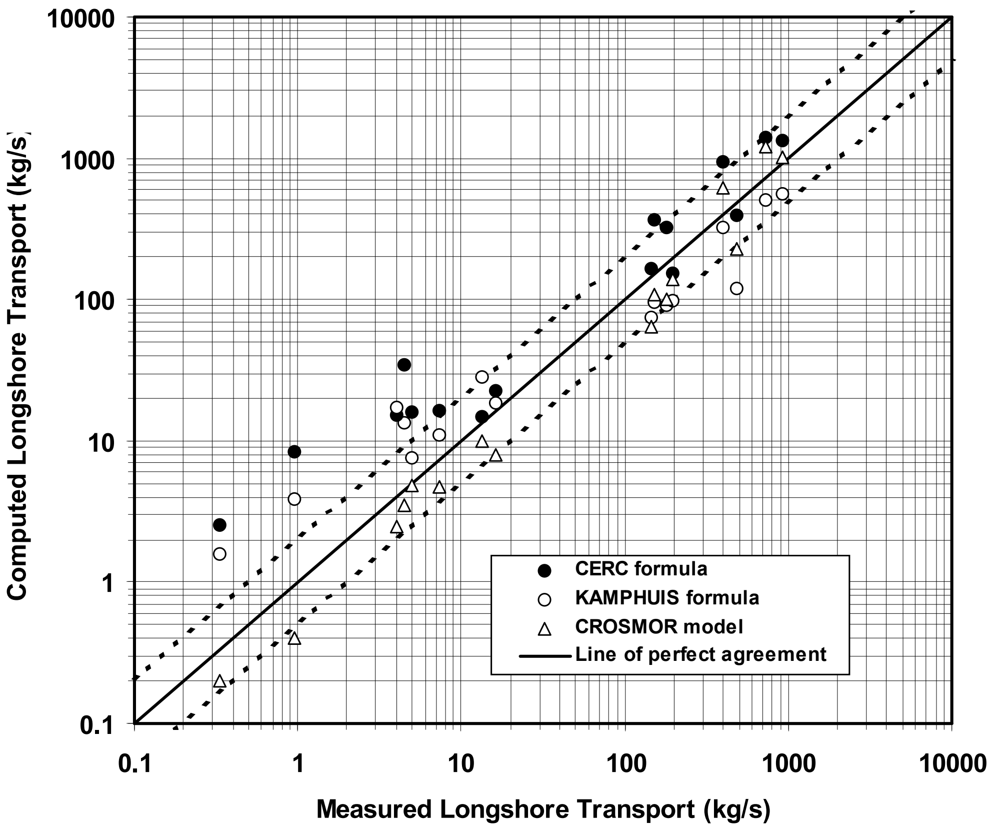

Figure 2 Comparison of measured and computed longshore transport rates

The CROSMOR2000 model also yields information of the cross-shore distribution of the computed wave height, longshore current velocity and longshore sand transport. An example for a storm event at the Duck site (USA) is given in Figure 3.

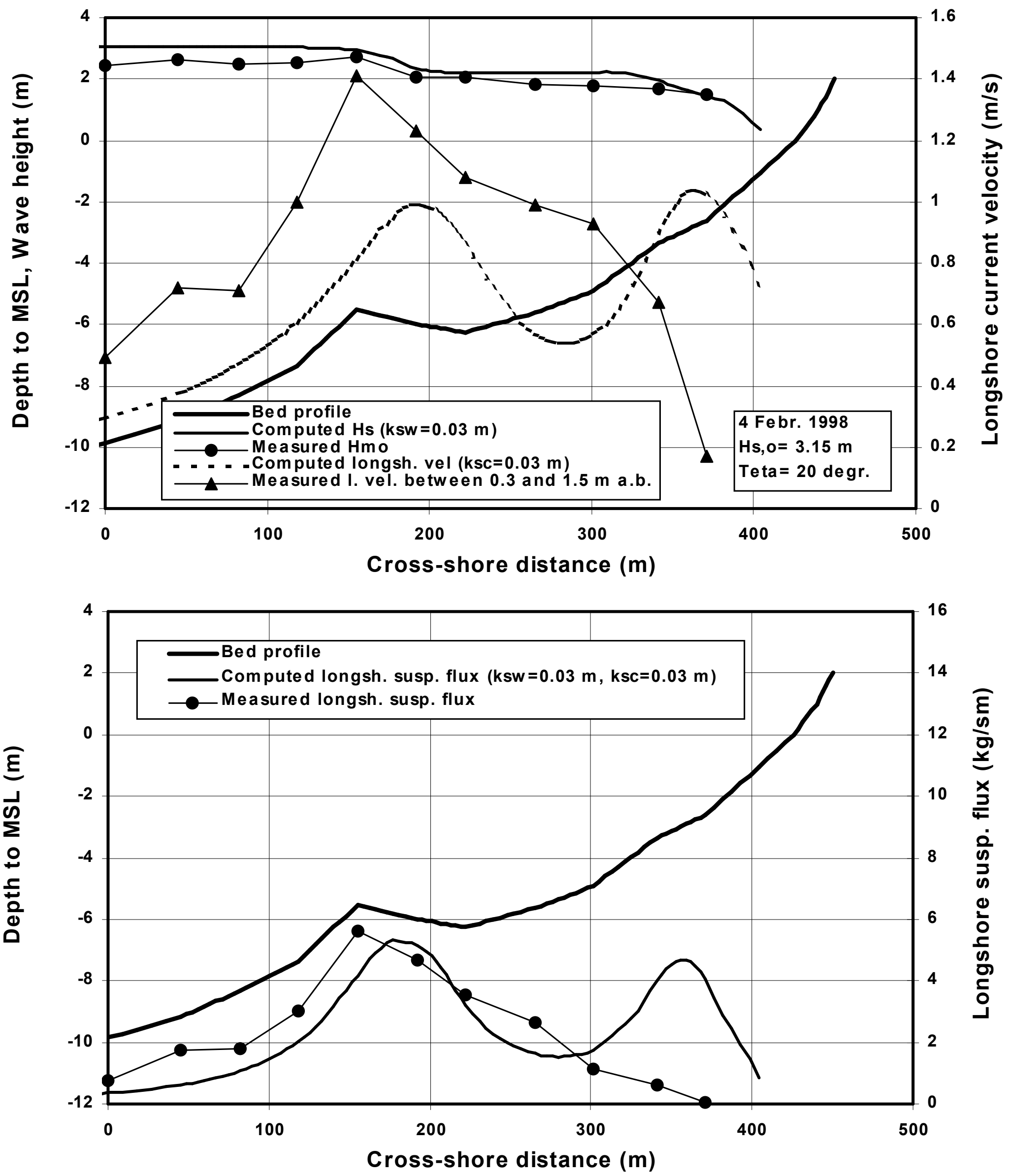

Figure 3 Wave height, longshore current velocity and sand transport along cross-shore profile of Duck site, 4 February 1998; d_{50}=0.15 mm (a.b.=above bed)

The computed wave heights are somewhat too large (20%) in the outer surf zone landward of the bar crest (6 m depth contour); the computed values are in good agreement with the measured values in the zone landward of the bar crest. The computed longshore current velocities are too small (20% to 40%) in the outer surf zone seaward of the 4 m depth contour; the model results show a peak in the inner surf zone, which is not observed. The computed longshore suspended sand transport rates are in reasonable agreement with measured values in the outer surf zone, but the computed values are much too large in the inner surf zone; most of the measured transport occurred in the outer surf zone seaward of the 4 m depth contour.

The CROSMOR model often yields a bimodal distribution of the longshore transport along the cross-shore bed profile with a major peak around the outer bar crest and a minor (second) peak in the inner surf zone.

DEVELOPMENT OF NEW SIMPLIFIED EQUATION FOR LONGSHORE SAND TRANSPORT

The simplified formula for the longshore sand transport (incl. all effects) reads as:

$$Q_{t,mass}= K_o\, K_{swell}\, K_{grain}\, K_{slope}\, (H_{s,br})^{2.5}\, V_{eff,L} \qquad (10)$$

with:

$Q_{t,mass}$ = longshore sand transport (in kg/s, dry mass);

$H_{s,br}$ = significant wave height at breakerline (m);

$V_{eff,L}$ $=[(V_{wave,L})^2+(V_{tide,L})^2]^{0.5}$= effective longshore velocity at mid surf zone (m/s) for tidal velocity and wave-induced velocity in same direction (minus sign for opposing conditions);

$V_{wave,\,L}$ $=0.3(gH_{s,br})^{0.5}\sin(2\theta_{br})$= wave-induced longshore velocity in mid surf zone (incl. wind effect);

$V_{tide,L}$ =longshore velocity in mid surf zone due to tidal forcing (=0 m/s for non-tidal cases; 0.1 m/s for micro-tidal, 0.3 m/s for meso-tidal and 0.5 m/s for macro-tidal cases);

θ_{br} = wave incidence angle at the breakerline (to shore normal; in degrees);

K_o = 42;

K_{swell} $=T_{swell}/T_{ref}$= swell correction factor for swell waves (<2 m); with T_{ref}= reference wave period= 6 s ; K_{swell}=1 for wind waves;

K_{grain} = $(d_{50,ref}/d_{50})$ = particle size correction factor ($d_{50,ref}$= 0.2 mm), with $K_{grain,min}$=0.1 for d_{50}>2 mm;

K_{slope} = $(\tan\beta/\tan\beta_{ref})^{0.5}$= bed slope correction factor ($K_{slope,max}$=1.25, $K_{slope,min}$= 0.75); $\tan\beta$=actual bed slope, $\tan\beta_{ref}$=0.01 (reference slope of Egmond profile); the overall profile slope is defined as the slope between the waterline and the 8 m depth contour; $\tan\beta$=8/B with B= distance between waterline and location of 8 m depth contour seaward of outer breaker bar); the beach slope of the inner surf zone slope can **not** be used in the slope correction factor!

For a zero tidal velocity ($V_{tide,L}$=0 m/s), d_{50}=0.2 mm, $\tan\beta$=0.01 and K_{swell}=1, Equation (10) reduces to Equation (7) substituting the expression (Equation 9) for longshore current ($V_{wave,\,L}$). Detailed information is given by Van Rijn (2001).

Assuming a straight uniform coast with parallel depth contours, the water depth at the breakerline (location where 5% of the waves are breaking) can be estimated from:

$$h_{br}= [(H_{s,o}^{\,2}\, c_o \cos\theta_o)/(\alpha\, \gamma^2\, g^{0.5})]^{0.4} \qquad (11)$$

The wave incidence angle at the breakerline (θ_{br}) can be determined from:

$\sin\theta_{br}=(c_{br}/c_o)\ \sin\theta_o$ (12)

with:

$H_{s,o}$ = significant wave height at deep water;

c_o, c_{br} = wave propagation speed at deep water and at breakerline;

θ_o, θ_{br} = wave incidence angle (to shore normal) at deep water and at breakerline;

γ $=H_{s,br}/h_{br}$= breaking coefficient based on 5% breaking= 0.4;

α = 1.8, calibration coefficient based on Egmond data;

L_o $=(g/2\pi)T_p^2$= wave length in deep water.

Determination of K-coefficients and validity ranges

The K-coefficients have been determined by analysing the computational results of the CROSMOR2000 model for a range of conditions. The base conditions are defined as:

- barred bed profile of Egmond (The Netherlands) characterized by two major bars;
- offshore wave climate defined at a depth of 15 m; the offshore significant wave heights are in the range of 1 to 5 m (wave periods between 5 and 9 s); the offshore wave incidence angles (to shore normal) are in the range of 10 to 70 degrees; the wave spectrum is represented by 9 classes based on a Rayleigh distribution;
- water level at 0.5 m above MSL;
- longshore velocity at the seaward deep water boundary between 0.5 m/s (for wave height of 1 m) to 1 m/s (for wave height of 5 m) due to tide-induced and wind-induced longshore currents; wind-induced effects are assumed to be dominant during storms;
- particle size of 0.2 mm and 0.4 mm;
- wave -related bed roughness ($k_{s,w}$) decreasing from 0.04 m (2D ripples) to 0.01 m (flat bed) for increasing wave height;
- current-related bed roughness increasing from 0.01 m (2D cross-shore ripples) to 0.04 m (3D mega ripples) for increasing wave height;
- water temperature of 10^o Celsius; salinity of 30 promille.

The offshore wave climate is defined at a depth of 15 m, because offshore wave conditions generally are measured by use of directional wave rider bouys or platform stations in depths of this order of magnitude (10 to 20 m). It should be realized that this depth is not really deep water for storm wave conditions.

To determine the correction factors (K) accounting for the effect of basic parameters, the following parameters have been considered:

- wave period of swell waves;
- particle size: the sediment particle size has been varied in the range of 0.15 mm to 10 mm for one wave condition (offshore wave incidence angle of 30 degrees and offshore wave height of 3 m);
- additional wind-induced and tide-induced longshore velocity at seaward boundary for various offshore wave conditions;
- profile shape, using profiles from three barred sites (Duck, USA; Egmond and Noordwijk, Netherlands) for various offshore wave conditions.

Particle size effect

Analysis of the model results for the particle sizes of 0.2 and 0.4 mm shows that the LST decreases by a factor of 2 to 3 for a change in particle size from 0.2 to 0.4 mm. The decrease in LST is largest (factor 3) for the larger waves ($H_{s,o}$>3m). The LST decreases strongly for particle sizes in the range between 0.15 and 10 mm, see Figure 4 based on CROSMOR2000 results. Roughly, it can be said that the longshore transport of shingle and gravel is a factor 10 smaller than that of sand for the same wave conditions.
The particle size correction factor K_{grain} has been set to a constant value of 0.1 for particle sizes larger than 2 mm. This means that the longshore transport of coarse material (>2 mm) based on Eq. (10) is assumed to be independent of particle size. For coarse materials the bed-load transport is dominant and not much dependent on particle diameter, which can be seen from existing bed-load transport formulae. A constant K_{grain}-factor may be realistic for the gravel and shingle range (2 to 50 mm), but it is not realistic for larger sizes (>50 mm). More study is necessary to determine a proper K_{grain}-factor, which can represent the particle size effect of all coarse materials, including a transition to conditions with immobile material.

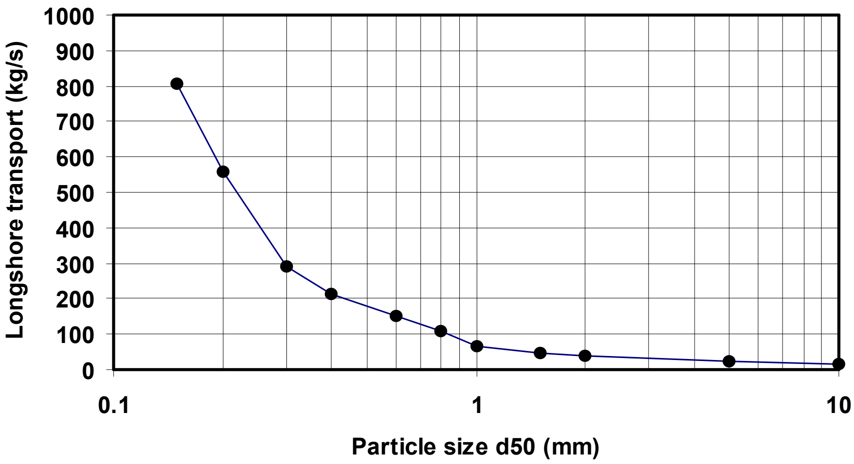

Figure 4 Effect of particle size on longshore transport,
offshore wave angle=30°, offshore wave height= 3 m at depth of 15 m

Equation (10) is valid for sand beaches and gravel/shingle beaches. To test the applicability of Eq. (10) for gravel/shingle beaches, two data sets have been used (Chadwick, 1989 for Shoreham coast, UK and Nicholls and Wright for Hurst Castle coast, 1991). The computed longshore transport values of gravel based on Eq. (10) are all within a factor of 2 of the measured values. On request of the present author, Chadwick has used Eq. (10) to evaluate whether it yields realistic results for the net annual longshore transport of shingle at the Shoreham coast (Pers. communication, 2001). Based on the measured wave climate at the site, the net annual longshore transport was computed to be about 14,000 m^3, which is in excellent agreement with the measured value of 15,000 m^3.

CONCLUSIONS

Field data of longshore transport

- the available field data sets cover a transport range from about 0.1 to 1000 kg/s or 5.4 to 54000 m^3/day (using a bulk density of 1600 kg/m^3);
- the field data suggest the presence of a relationship between transport (kg/s), wave height and wave incidence angle, as follows: $Q_{t,mass} = 40(H_{s,br})^3 \sin(2\theta_{br})$;
- the field data sets do not show any systematic influence of particle size and beach slope;
- the longshore velocities are 0.5 to 1 m/s (minor storms) and 1 to 1.5 m/s (storms).

Model verification results based on field data

- the CERC formula yields results, which are slightly too large (factor 2) compared with measured values for storms but much too large (factor 5) for low wave conditions;
- the KAMPHUIS formula yields results, which are slightly too small (factor 1.5) for storm conditions but much too large (factor 3) for low wave conditions;
- the CROSMOR2000 model yields results, which are slightly too large (factor 1.5) for storm conditions and somewhat too small (factor 2) for low wave conditions; a quasi-regular wave approach yields the best results for swell-type wave conditions.

Parameterisation results

- the LST of sediment of 0.2 mm along a barred profile varies in the range of 5 to 5,000 kg/s (300 to 300,000 m^3/day) for wave heights in the range between 1 and 5 m and wave incidence angles between 10^o and 70^o at depth of 15 m;
- the LST varies with the wave period: an increase or decrease of the wave period of about 10% to 20% (at the same wave height) leads to an almost constant longshore current velocity and sand transport, but the longshore sand transport becomes almost twice as large for long-period swell waves; this effect can be represented in the simplified equation by means of a correction factor;
- the LST varies strongly with particle size; the LST increases significantly for particle sizes smaller than about 0.3 mm due to dominance of the suspended load transport process and decreases for particle sizes larger than 0.3 mm; the LST of shingle and gravel roughly is a factor 10 smaller than that of sand for the same wave conditions; the particle size effect can be represented by means of a size- dependent correction factor;
- the effect of the additional longshore velocity (at seaward boundary) is largest for a small wave incidence angle, because the wave-induced longshore velocity is relatively small for a small wave incidence angle; the longshore transport of the base run is significantly larger (up to 50%) by including an additional velocity due to tide and wind effects for conditions with relatively small offshore angles of 5^o and 10^o; the effect of the additional longshore velocity is less important for offshore wave angles larger than about 20^o, particularly for storm conditions when wave-induced forcings are dominant;
- the LST is significantly affected by the profile shape; a relatively steep profile (Duck profile) leads to somewhat larger wave heights at the breakerline and somewhat larger longshore current velocities and transport rates in the surf zone, compared with the values at the more gentle Egmond profile; similarly, a relatively flat profile (Noordwijk profile) leads to smaller wave heights at the breakerline and smaller longshore current velocities and transport rates in the surf zone; these effects can be represented by an overall bed slope factor.

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