CHAPTER 144

TOWARDS MODELLING COASTAL SEDIMENT TRANSPORT

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Abstract

Sediment transport data from the field and laboratory tests are used to gain insight into two fundamental questions. Firstly: What is the relative importance of coexisting waves and currents for the resulting sediment transport? Secondly: Is the influence of grain size as strong as traditional models predict, or is it as weak as the empirical CERC-formula indicates?

Wave tank data reveal that the oscillatory velocity will in most cases determine the direction as well as the magnitude of the shore normal sediment transport, and wave flume data on shore normal transport as well as field data on littoral drift show weaker grain size dependance than traditional sediment transport models predict. It is suggested that wave dominance as well as weak grain size dependence are manifestations of the fact that the dominant transport mechanisms are often more organised than the diffusion process on which many traditional models are based.

1. Introduction

The relative importance of waves, or more specifically the oscillatory velocity component $\tilde{u}(z,t)$, and steady currents $\bar{u}(z)$ has been the subject of considerable research and discussion. The conclusion of most of the theoretical work has been that the currents should be the most important with respect to the actual transport while u may well be the dominant factor in the entrainment process. Recent experimental work has shown however that the transport component resulting from the product of the oscillatory components of concentrations and velocities $(\overline{\tilde{u}\tilde{c}})$ is often more important than $\bar{u}\,\bar{c}$. Examples of this evidence will be discussed below.

In this context it is of course important to acknowledge the fact that different types of steady currents will have different potential for transporting sediments depending on their strength close to the bed where the sediment concentrations are largest. For example, the steady boundary layer currents which are generated by the waves will generally be much stronger at the bed than currents which are driven by a uniform pressure gradient such as tidal currents or undertow, but they may not be apparent from measurements taken above the wave boundary layer.

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Some insight into the problem of grain size dependance was gained by the study of Nielsen (1988) which tested three different models against wave flume data on shore normal transport. The first of these models is a diffusion model developed along the lines suggested by Nielsen et al (1978) and by Nielsen (1979). The second model is inspired by the "heuristic model" of Dean (1973) and the third is based on a simple "grab and dump" concept. The third model is much simpler than the two others, but it is also more reliable. More specifically, it shows a more realistic grain size dependence of the resulting transport than the two more traditional models. The traditional models tend to predict by far too strong decline of the sediment transport rate with increasing grain size.

Although the logical connection is not very direct it is interesting to note that a similar situation can be observed with respect to the total longshore transport or littoral drift. That is, existing traditional models like that of Deigaard et al (1987), which should be valid for a fairly common type of surf zones, predict a strong grain size dependence while the data, as presented in the Shore Protection Manual show no grain size dependence at all (see Figure 1).

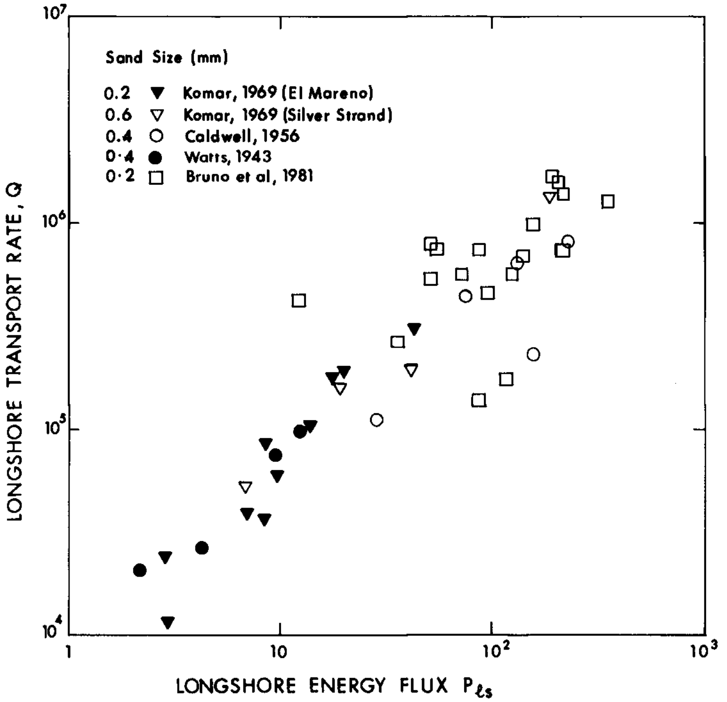

Figure 1: Littoral drift data as function of the longshore wave energy flux (from CERC 1984). The data shows no significant grain size dependance for the measured littoral drift.

To this which we may call "The C.E.R.C. formula paradox" one of the following explanations may apply:

1: The data is unreliable.

2: The processes modelled by Deigaard et al (1987) were not dominant in the surf zones where the measurements were made.

2. Relative Importance of uc and uc

Figure 2 is an illustration of the relative importance of waves ($\tilde{u}(z,t)$) and a superimposed steady current ($\bar{u}(z)$) for the sediment transport along a wave flume.

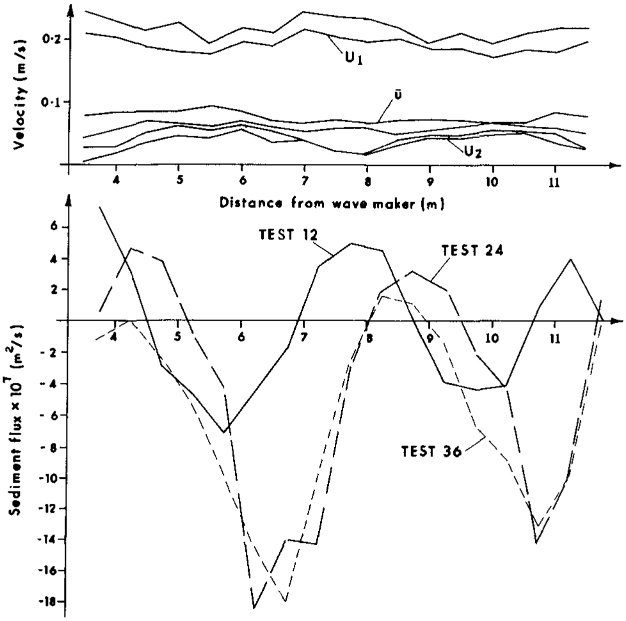

Figure 2: Wave flume sediment transport experiments by Schepers (1978). The hydrodynamic conditions (top) were similar in the three tests: T=1.5 s, and D=0.30 m. The envelopes of the velocity magnitues u, U_1, and U_2 are plotted as function of distance from the wave maker and were all measured 0.1m above the bed. The sediments had the following characteristics (d,w): Test 12: (0.125mm, 0.010m/s), Test 24: (0.250mm, 0.028 m/s), Test 36: (0.465mm, 0.050 m/s). The corresponding measured net sediment fluxes (bottom) show three important facts: (1) Even though the measured current u(0.1) is always positive (shoreward), the sediment transport is predominantly negative. (2) The measured transport rates are of very similar magnitude despite the large difference in grain sizes. (3) The transport pattern for the coarser sand (d/A>0.004) is shifted relative to that of the finest, probably because acceleration effects become more important relative to velocity magnitude with increasing grain size.

In the top part of the figure are shown the measured velocity components $\bar{u}$, U_1 and U_2, where U_1 is the amplitude of the fundamental mode of the wave motion and U_2 is the amplitude of the second harmonic. The velocities were measured ten centimetres above the bed. The bottom part of the figure shows the corresponding, measured sediment transport rates. The experiments were carried out at the Delft University of Technology and have been described in more detail by van de Graaff and Tilmans (1980).

The first thing to note about the measured sediment transport rates is that although the steady current ten centimetres above the bed was at all points shoreward, the measured transport rates were predominantly offshore. Thus, the current velocity ten centimetres above the bed is no indicator for the direction of the resulting sediment transport.

For three dimensional situations there is also evidence that the waves are more dominant than one might have expected with respect to transport capacity. For example Davison (1987) has reported on tracer experiments where the centroid velocity as well as the larger axes of the "tracer ellipses" always tended to be in the wave direction rather than in the direction of the tidal currents. It is not clear from these experiments however if the transport is actually carried by u or by the steady wave induced boundary layer drift.

3. Sediment Transport in Pure Oscillatory Flow

In order to be able to model coastal sediment transport in general, it is important to understand how sand is transported in a purely oscillatory flow, i.e. a flow where $\bar{u} \equiv 0$; but it can be difficult to generate such a flow in wave tanks because of wave induced mass transport. Most important in this context is the boundary layer drift under progressive waves which was described by Longuet-Higgins (1956).

However, in oscillating water tunnels, where the water motion is horizontally uniform this drift should not occur. Therefore, the oscillatory water tunnel (OWT) provides the best experimental facility for studying sediment transport in purely oscillatory flow.

Sato (1986) performed sediment transport experiments in an OWT which are of interest in this context. He found that with water velocities of the "Stokes-wave-type" i.e. with

$$u(t) = U_1 \cos \omega t + U_2 \cos 2\omega t \qquad (1)$$

the resulting sediment transport was always "seaward" that is in the direction opposite to the largest instantaneous velocity.

This result is to some extent in conflict with the field observations of Doering and Bowen (1988) who found that the correlation between instantaneous velocities and concentrations was positive which means that the net sediment flux at the measuring point tended to be in the direction of the largest instantaneous velocities.

When the two authors found opposite results, it is most likely due to the fact that the bed forms were different in their experiments.

In Sato's tests the bed was covered by regular, sharp crested ripples while Doering and Bowen's field tests would have involved bed forms that were flatter and more rounded.

The trend found by Sato for sediment transport over sharp crested ripples is also apparent in the numerous wave flume tests of Vellinga (1975), Schepers (1978) and Tilmans (1979) which were analysed and modelled by Nielsen (1988). That is, those test show a clear tendency for the resulting transport to go in the direction opposite to that of the largest velocities. The reason for this is that the transport over sharp crested ripples is a two step process where the sand is not carried very far by the velocities which activate it. It is trapped behind the ripple crest and then later released to be transported in the opposite direction after the flow reversal.

While the results from Sato (1986) and those analysed by Nielsen (1988) show that velocity-moment-models like that of Bailard and Inman (1981) predict transport in the wrong direction over sharp crested ripples, such models might apply over more rounded bed forms.

4. Grain Size Dependence of Shore Normal Transport

Nielsen (1988) used three different approaches for modelling the Dutch flume experiments. The first was the traditional diffusion approach, the second was a heuristic entrainment and settling approach similar to that of Dean (1973) and the third was an ultra simplistic "grab and dump" model.

All of the models were quantified in terms of parameters from the steady concentration profiles only; that is, the reference concentration Co and the vertical length scale L_s defined by:

$$\bar{c}(z) = C_0 \exp[-z/L_s] \qquad (2)$$

All of the three modelling approaches were reasonably successful and this shows the comforting fact that the immense complexity of the variation of c(z,t) needs not be considered explicitly in order to obtain reasonable results. Only the time averaged concentration profile $\bar{c}(z)$ is needed, and fortunately experimental data on $\bar{c}(z)$ is abundantly available.

The model results can be summarised as follows:

Diffusion model: $Q = C_0 L_s U_1 S\left(\frac{Umax}{Umin}\right) F_d\left(\frac{Ls}{wT}\right)$

Heuristic entrainment model: $Q = C_0 L_s U_1 S\left(\frac{Umax}{Umin}\right) F_e\left(\frac{Ls}{wT}\right)$

Grab & Dump model: $Q = C_0 wAS\left(\frac{Umax}{Umin}\right)$

Where U_1 is the velocity amplitude of the fundamental mode of the wave motion, U_{max} and U_{min} are the extreme shoreward and seaward velocities respectively, w is the sediment settling velocity, A is the water particle semi excursion and T is the wave period.

The skewness function S(Umax/Umin) was the same in all models and the two functions F_d and F_e of the time scale ratio L_s/wT are quantitatively similar.

From these formulae we can see how the resulting sediment flux Q depends on grain size with all other things being equal. Because C_0 and L_s are both decreasing functions of the grain size we see that the two first models predict a fairly strong decrease in Q for increasing grain size, while the "grab and dump" model predicts a more moderate grain size dependance. It turns out that the data basically confirm the weak grain size dependance predicted by the grab and dump model, see Figure 2 and Nielsen (1988) for more detail.

In essence the "grab and dump model" differs from the two more traditional models by assuming a more organised mode of transport. It basically assumes that the sand is moved in parcels. Inspection of the transport process for fairly coarse sand ($U_1/w<10$) over rippled beds confirms that it does in fact have this kind of nature. For finer sand, the organised nature is not obvious, but the "grab and dump model" will still work (see Nielsen 1988).

The trapping mechanisms by which a vortex dominated flow can keep sand in suspension and transport it very effectively were described by Nielsen (1984). However, for fine sand ($U_1/w>10$) the sand will on the average stay in suspension much longer than the life time of the vortices, and the success of the "grab and dump model" may thus be somewhat fortuitious for fine sand.

5. CONCLUSIONS

From the presently available data the following conclusions can be drawn about the relative importance of steady and oscillatory flow components with respect to sediment transport. For non breaking waves over horizontal beds the influence of, even fairly strong, currents is insignificant, see Figure 2.

Davison (1987) found that in an environment with tidal currents of similar though slightly smaller magnitude running perpendicular to the waves, the sediment transport inferred from radioactive tracers was always in the wave direction.

The role of the wave induced boundary layer drift over natural sand beds is however virtually unresolved. This is basically because these current themselves are not well known. The model of Longuet-Higgins (1956) is not known to be valid for turbulent boundary layers, and more recent "turbulent" models like that of Jacobs (1984) are not known to be valid for the relative roughness range which is typical for natural sand beds.

The transport due to purely (or almost purely) oscillatory flows over sharp crested bed forms goes in the direction apposite to that of the largest instantaneous velocities. This tendency may be reversed for rounded bed forms and flat beds so that velocity-movement-models like that of Bailard and Inman (1981) could apply to such situations.

Laboratory data on shore normal sediment transport (Figure 2) show a weaker grain size dependance than classical transport models would predict, and interestingly, the same is true for the litoral drift data shown in Figure 1. Judging from the results of Nielsen (1988) it might be inferred that the weak grain size dependence is due to the efficiency of highly organised transport modes which dominate the transport of coarser sediments.

It is not obvious that the implications from Nielsen (1988)'s study can be applied directly to the "CERC formula paradox" for littoral drift but it is possible that more organised (than diffusion) modes of transport tend to dominate for coarser sand and that such dominance leads to weak grain size dependance for littoral drift as well as for shore normal transport.

REFERENCES

Bailard, J.A. and D.L. Inman (1981): An energetics bedload model for a plane, sloping beach : local transport. Journal of Geophysical Research, Vol 86, pp 2035-2043.

C.E.R.C. (1984): Shore Protection Manual. Fourth Edition, Vol.1.

Davison, A. (1987): A radioactive tracer study of sand-seagrass dynamics, in the nearshore region of Holdfast Bay, South Australia. Australian nuclear science and technology organisation. Lucas Heights Laboratories. ANSTO/C67.

Dean, R.G., (1973): Heuristic model of sand transport in the surf zone. Proc. First Australasian Conf. Coastal Eng., Sydney, pp. 208-214.

Deigaard, R., Fredsoe, J. and Hedegaard I.B., (1986): Mathematical model for littoral drift. Journal of waterway, port, coastal and ocean engineering. (A.S.C.E.), Vol. 112, No. 3, pp. 351-369.

Doering, J.C. and A.J. Bowen (1988): Wave induced flow and nearshore suspended sediment. Proc. 21st Int. Conf. on Coastal Engineering, Torremolios.

Graaff, J. van de and Tilmans, W.M.K., (1980): Sand transport by waves. Proc. 17th Int. Conf. Coastal Eng., Sydney, pp. 1140-1157.

Jacobs, S.J., (1984): Mass transport in a turbulent boundary layer under a progressive water wave. Journal of Fluid Mechanics, vol 146, pp 303-312.

Longuet-Higgins, M.S., (1956): The mechanics of the boundary layer near the bottom in a progressive wave. Proc. 6th Inc. Conf. on Coastal Engineering, Florida, pp 184-193.

Nielsen, P., (1979): Some basic concepts of wave sediment transport. Series Paper 20, Institute of Hydrodynamics and Hydraulic Engineering (ISVA), Technical University of Denmark.

Nielsen, P., (1984): On the motion of suspended sand particles. Journal of Geophysical Research, Vol 89, No C1, pp 616-626. Erata: Vol 90, No C2, pp 3255-3256.

Nielsen, P., (1988): Three simple models of wave sediment transport. Coastal Engineering Vol. 12, pp.43-62.

Nielsen, P., Svendsen, I.A. and Staub, C., (1978): Onshore-offshore sediment transport on a beach. Proc. 16th Int.Conf. Coastal Eng., Hamburg, pp. 1475-1492.

Sato S. (1986): Oscillatory boundary layer flow and sand movement over ripples. Ph. D. Thesis, Dept. of Civil Engineering, University of Tokyo.

Schepers, J.D., (1978): Zandtransport onder invloed van golven en een eenparige stroom bij varierende korreldiameter. Masters Thesis, Delft University of Technology.

Tilmans, W., (1979): Zandtransport in de golfrichting in relatief ondiep water. Masters Thesis, Delft University of Technology.

Vellinga, P., (1975): Zandtransport door golven en de invloed van stoorgolven.