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NEAR-FUTURE NEEDS OF NUMERICAL MODELS OF LITTORAL PROCESSES

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ABSTRACT

An attempt is made to establish some connections between features of sediment motion in the 3 layers generally considered (fluid layer, bed layer, subsoil layer).

Sheet flow is found to be a very common feature of sediment motion in the bed layer. Vertical wave-induced pressure gradients acting at the bed surface of the subsoil layer are found to be capable of inducing sediment motion in offshore direction.

1. EVOLUTION OF MODELS

Three generations of numerical models of littoral processes can be distinguished, according to the number of dimensions they consider.

1.1 1D MODELS

A first generation of models establishes a direct link between hydrodynamics (waves) and morphology (shoreline response).

The 1D models, so called one (and more) line models, were originated by Pelnard Considere (1956) on the assumption that littoral drift is proportional to wave incidence.

Recently a more sophisticated sediment transport formulation was introduced along with shoreline/wave pattern interactions.

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Presently, the first generation models have entered the engineering stage which means that these models have been made sufficiently user-friendly to be used in engineering practice with a well-known (rather than acceptable) degree of accuracy (Hanson, 1988, Larson et al, 1987).

1.2 2D MODELS

A second generation of models tries to introduce the effect of currents generated by tide, wind and waves in 2DH models. Hence, much effort had to be put into hydrodynamics before any sediment transport could be computed.

Most researchers use clever but rather crude transport formulae such as Bijker's. However, it must not be forgotten that those formulae were derived from river engineering. Even in this field, which might appear quite simple to coastal engineers since there are only currents to deal with, river engineers are not always very sure about their predictions of bed roughness.

River formulae do not yet lead to accuracies much better than a factor 2 (if not 5) in the computation of sediment transport.

Hence, it is felt that there is a need for a more fundamental approach, in order to acquire a better understanding of reality rather than feeding some new coefficients into existing formulae.

Bakker (1974) opened the way to 2 DV models calculating time and space variations in sediment concentration during one wave period, taking into account the time variation in the eddy viscosity, in other words, turbulence models were introduced based on the diffusion principle.

This would lead to the one-equation model by Fredsoe (1985) and is going to lead to the introduction of more sophisticated two-equation ($k - \varepsilon$) models (Justesen, 1988) into 2 DV sediment concentration models.

1.3 3D MODELS

A third generation of models, not yet operational, will soon appear as a consequence of the above-mentioned developments, as a link between 2 DH and 2 DV models.

We seem to be about to start up very large and expensive research projects on 3D turbulence models, and the time may have come to ask a few questions.

1.4 DISCUSSION

Much attention has been devoted in recent years to hydrodynamics in the second generation models. This certainly was and still is necessary. However, it is not allowed to accept any risk of disconnection between hydrodynamics and sedimentology: what if the sediment transport formulation appears to require other (yet unknown) parameters?

It must be borne in mind that the target is not hydrodynamics in itself, but coastal morphology.

A few examples can be given which sound as warnings.

a) Van der Graaff (1986) pointed out that the common assumption that hydrodynamic and sediment diffusion coefficients are equal may be quite erroneous. As a matter of fact he found some quite unexplained features.

b) In his discussion, Randkivi (1976) points out that 'the use of clear water values can hardly be justified from a theoretical point of view because even the mean velocity profile is appreciably changed by the presence of suspended sediment'. This turns out to a reduction of von Karman's constant when a logarithmic profile is assumed (down to 0.21 with an average sediment concentration of 15.8 g/l).

   Furthermore, 'it appears that the suspended sediment causes changes in the structure of turbulence. The dispersed matrix of solids acts as a screen through which the fluid flows and reduces the scale of turbulence, that is the amplitude of fluctuations'. On the other hand 'the intensity may even be increased when the movements are intense enough for the particles to form wakes'.

c) The main limitations of the diffusion principle are its (probable) inability to deal with the various types of breaking waves and its requirement for a sediment concentration value at bed level as a boundary condition.

   As far as breaking waves are concerned, it seems likely that the energy principle will lead to some useful indications regarding the total amount of suspended sediment, but not on its vertical distribution (Bagnold, 1988).

   Concerning sediment concentrations at bed level, there is a real need for more fundamental physics.

In the next section, a further look into sediment motion at bed level will be given, focussing on one of the many forces acting on sediment particles, i.e. vertical wave-induced pressure gradients in the subsoil. The next section will be concluded by a few notes concerning the swash zone.

2. FEATURES OF SEDIMENT MOTION

2.1 SUBDIVISION OF FEATURES

It is tempting to subdivide features of sediment motion into 3 layers:

a) A fluid layer which includes 90% or more of the waterdepth. This layer is described well by conventional clear water hydrodynamics along with diffusion of suspended sediment under the action of turbulence.

b) A bed layer which includes high sediment concentration and a close, yet not well defined, interaction between fluid and sediment.

c) A subsoil layer which is considered as stable from the sediment transport point of view but which is certainly not inert, since the soil skeleton is compressible and pore water moves inside it.

It is possible to name the leading scientists working on each of the 3 layers: Bakker, and more recently Fredsoe, on the fluid layer; Bagnold, and more recently Horikawa and Bakker, on the bed layer; Madsen on the subsoil layer.

2.2 FEATURES OF SEDIMENT MOTION IN THE BED LAYER

In Horikawa's recent review (1988), Ogawa and Shibayama present much information from which it appears that features of sediment motion are well described by Shield's parameter, defined as follows for oscillatory flow:

$$\psi_m = \frac{f_w \hat{U}_b^2}{2\Delta g D}$$

where:

f_w: Jonsson's (1966) wave friction factor [-]

$\hat{U}_b$: Maximum near bottom wave velocity [m/s]

Δ: Relative density of sediment $((\rho_s-\rho_w)/\rho_w)$ [-]

g: Gravitational acceleration [m/s²]

D: Sediment diameter [m]

It appears that 3 main features can be distinguished:

. initiation of motion, for $\psi_m = 0.03$ to 0.08

. rippled bed, for 0.03 to $0.08 < \psi_m < 0.4$ to 0.7

. sheet flow on flat bed, for $\psi_m > 0.4$ to 0.7

It is realised that this may be a bit simplistic, since a parameter like $\hat{U}_b/W$ (W: sediment particle fall velocity) is also important.

The point, however, is to show under what wave conditions each feature is likely to appear in nature.

It is therefore assumed, again for simplicity, that waves are purely sinusoïdal.

Figure 1 shows the result for $f_w = 0.08$ and $d/D = 10^4$ (d: water depth, H: wave height, Lo = deep water wave length, $k = 2\pi/L$, L: local wave length).

It should be noticed that the right hand side of the curves are aborted by the physical limit of maximum wave steepness.

It appears that sheet flow occurs for $H/d > 0.1$, that is for $H > 0.4$ m with $d = 2$ m, $T = 2.5$ s and $D = 0.2$ mm which may be considered as rather mild wave conditions.

Hence, sheet flow appears to be a very common feature.

It should be realised that this bed layer is very thin: 10 to 15D, that is only a few millimetres, but sediment concentrations are very high.

The maximum theoretical concentration of spheres lies between the following limits:

. tetrahedral pilling: $C_{max} = \pi\sqrt{2}/6 = 74\%$

. cubic pilling : $C_{max} = \pi/6 = 52\%$

The maximum concentration in nature appears to be about 62%, since the porosity of natural loose packed sand is generally accepted to be 38%. This concentration yields 1640 g/l.

This kind of concentration is obviously about 1000 times higher than in the fluid layer, i.e. even if the flow velocity in the bed layer is 10 times smaller than in the fluid layer, the sediment transport in a 1 cm thick bed layer equals that of a 1 m thick fluid layer.

The pioneering work by Bagnold, and by Bakker (1986, 1988) in his footsteps, is clearly of some importance here.

2.3 PARTICLE STABILITY

The forces involved in particle stability on the bottom may be summarised as follows (after Randkivi, 1976, pp. 342 - 344):

- Gravity: particle's own mass.
- Added mass of fluid to be moved.
- Drag:
  - surface drag in laminar flow
  - surface and form drag in turbulent flow
- Lift:
  - shear lift
  - magnus lift for spinning particles
- Pressure gradient over particle.
- Reaction forces on neighbouring particles.
- Rolling friction.

and the inertia force which is equal and opposite to the resultant of all other forces.

The one force which will be further investigated here is the pressure gradient, not the commonly known horizontal pressure, but the vertical one, that is the vertical pressure which is generated in the subsoil layer under wave action. This appears to be the only vertical force which is specific to wave action, i.e. this vertical force does not exist in steady flow conditions.

Entering the field of flow in the porous subsoil, we are concerned with pressure gradients and especially with the vertical pressure gradient at the bed surface. Hence, we define:

$$i_{\perp} = \frac{1}{\rho g} \left(\frac{dp}{dz} \right)_{z=0}$$

Madsen (1978) presents a general theoretical analysis of flow induced in a porous bed taking into account the effects of compressible pore fluid, compressible soil skeleton and anisotropy.

Again for simplicity, we consider his solution for incompressible pore fluid and soil skeleton in the case of isotropic soil.

Then, the wave induced pore pressure is:

$$p = p_o \ e^{kz}$$

where:

p_o is the wave-induced pressure at the bed surface ($z = 0$) and $k = 2\pi/L$.

Hence:

$$i_\perp = \frac{kp_o}{\rho g}$$

Assuming linear waves, the results shown in figure 2 are found.

It is noticed that water level, orbital velocity and vertical pressure are in phase, i.e. the maximum upward pressure gradient at the bed surface occurs at the same time as the wave trough and the maximum offhsore orbital velocity. This means that if the vertical pressure gradient is able to lift a particle, it will be washed away in the offshore direction.

The following two criteria may be considered for stability of a particle on the bed surface. Both criteria are deduced from soil mechanics.

a) Fluidisation condition

Let us consider the vertical stability of a saturated sand column with height h_o and porosity η. The vertical forces acting on it are:

- gravity: $[\eta\rho_w + (1-\eta)\rho_s]gh_o$
- water pressure: $\rho_w g(h_o+h_1)$

where (h_o+h_1) is the water pressure exerted on the bottom of the sand.

In a state of equilibrium both forces are equal and it is found that:

$$i_\perp = \Delta(1-\eta)$$

with $i_\perp = h_1/h_o$ and $\Delta = (\rho_s-\rho_w)/\rho_w$.

For natural sand, $\eta = 0.38$ and $\Delta = 1.65$, so that $i_\perp = 1$. This is known as the fluidisation condition since for $i_\perp > 1$ quicksand will occur.

b) Rolling condition

Madsen (1978) gives a stability criterion which is deduced from Mohr's circles introducing the angle of internal friction (ϕ) and Poisson's ratio (μ):

$$i_\perp = \frac{\sin\phi - (1-2\mu)}{2(1-\mu)}$$

The stability limits shown in figure 2 are based on $\mu = 0.3$ and $\phi = 30$ to $35°$ for cohesionless sand.

It can be seen that instability according to the above rolling condition may be reached quite often in nature near the breaker zone.

Moreover, Madsen states that pore fluid and soil skeleton compressibility induce higher pressure gradients near the bed surface, especially with fine material (smaller than say 0.5 to 1 mm).

Thus $i_\perp$ might well become larger than 1, leading to fluidisation of the bed surface.

It may be concluded from this section that the wave-induced vertical pressure gradient is certainly not a negligible quantity in the set of forces involved, since it is capable of producing 10 to may be 100% of the total weight of the surface layer of the subsoil in the vicinity of the breaker zone.

2.4 MOTION IN THE SWASH ZONE

On this part of the beach waves can be observed to rush up and down the slope. Uprushing waves look like small bores moving up on a dry bed or in shallow water.

It can be observed very clearly that onshore sediment transport with uprush is mainly in suspension: many sediment loaded vortices can be clearly distinguished and must result from residual turbulence after breaking of waves.

During the downrush phase a completely different feature arises as sediment transport can be clearly seen as bedload only.

It would appear that on the reversal of flow from uprush to downrush, all the sediment is thrown to the bottom and turbulence vanishes.

Katori's measurements reported by Horikawa (1988) seem to confirm these observations.

3. CONCLUSIONS

An attempt has been made to establish some connections between features of sediment motion in the 3 layers generally considered:

- fluid layer (suspended load),
- bed layer (bed load),
- subsoil layer (source of sediment).

It was found that sheet flow in the bed layer is a very common feature of sediment motion and that an increased research effort should be directed to this area.

It was found also that vertical wave-induced pressure gradients act at the bed surface of the subsoil layer. This force might well be capable of lifting particles from the bed surface. Since this force is in phase with orbital velocity, the maximum lift occurs when the maximum orbital velocity is directed offshore, leading to potential offshore sediment motion.

Finally, some observations of sediment motion in the swash zone indicate suspended load with uprushing waves and bed load with downrushing waves.

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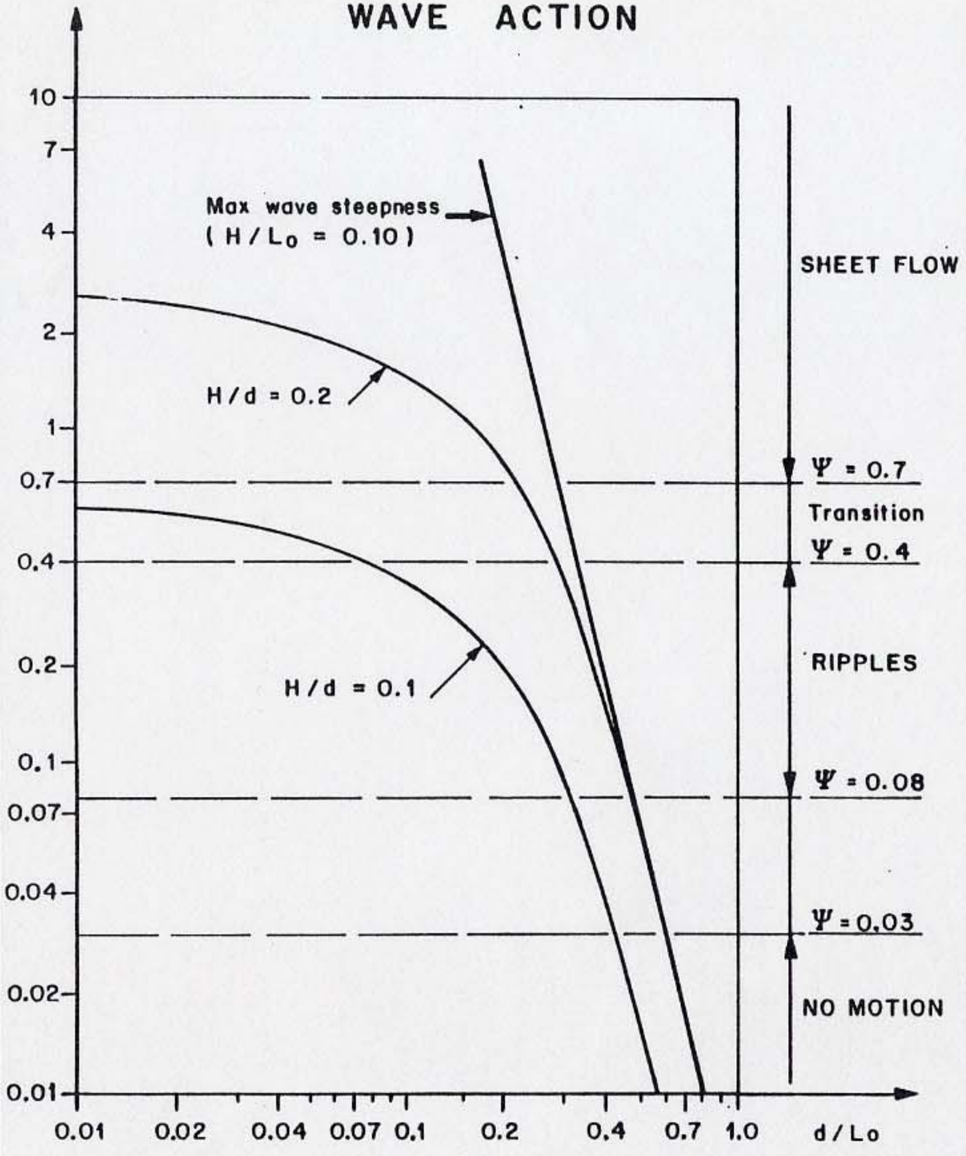
Fig. 1

SEDIMENT MOTION UNDER WAVE ACTION



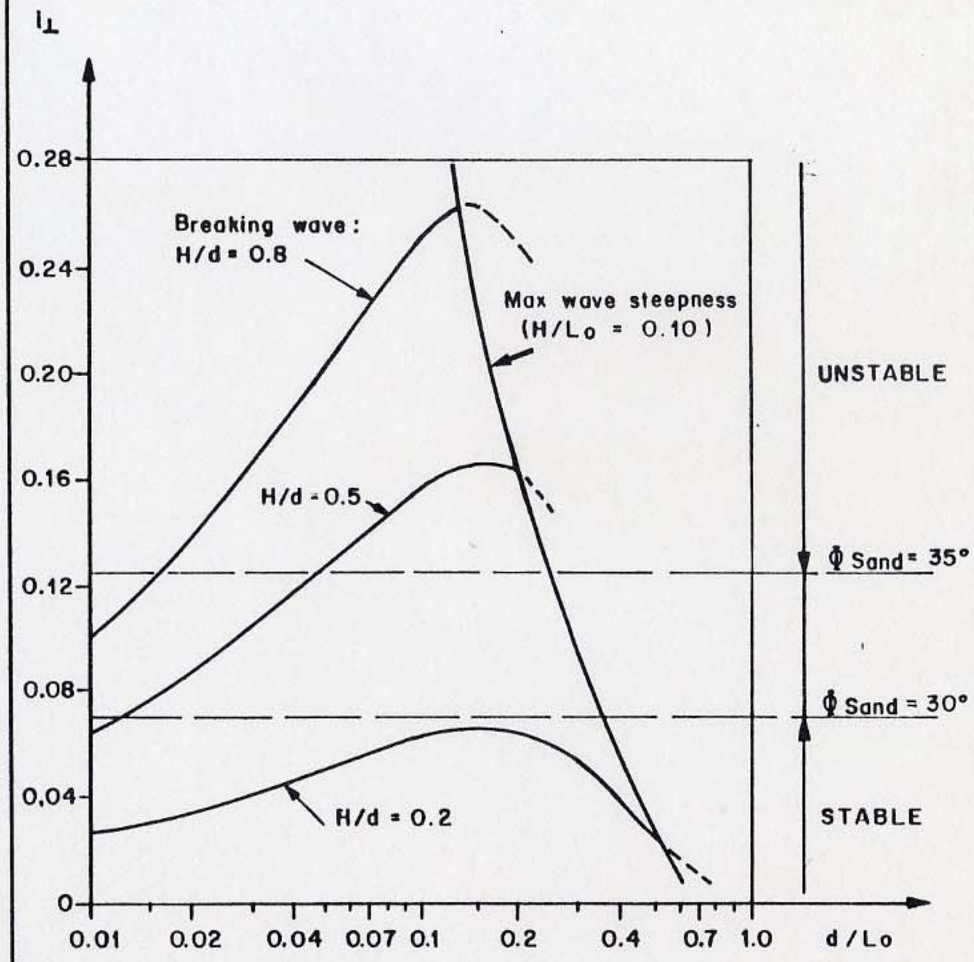
$\frac{d}{D} = 10^4$	$f_w = 0.08$ $\Delta = 1.65$

Shield's parameter for waves :

$$\Psi_m = \frac{f_w\,\hat{u}_b^2}{2\,\Delta g D} = \frac{f_w}{2\Delta}\cdot\left(\frac{H}{d}\right)^2\cdot\frac{d}{D}\cdot\frac{\pi d}{2 L_o \sinh^2 kd}$$

Fig. 2

VERTICAL PRESSURE GRADIENT AT BED SURFACE



Incompressible pore water and soil skeleton

$$i_\perp = \frac{k p_o}{\rho g} = \frac{H}{d}\cdot\frac{\pi d}{L \cosh kd}$$