Laboratory Experiments and the Development of Wave-Driven Sand Transport Models

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Abstract

The paper presents an overview of results from large-scale laboratory experiments on sand transport processes under sea waves. The experiments, especially those carried out in recent years in the Aberdeen Oscillatory Flow Tunnel at Aberdeen University and the Large Oscillating Water Tunnel at Delft Hydraulics, provide insights into the underlying processes for both the ripple and sheet flow regimes. Insights and data from the experiments are used to inform the development of predictive models. The paper includes an account of recent modeling developments, especially of semi-unsteady models used for practical applications.

Key words: laboratory experiments, sediment transport, waves, oscillatory flow, ripples, sheet flow.

1. Introduction

Sand transport under sea waves is determined by processes occurring close to the seabed, often within the bottom few centimetres where vertical gradients of flow velocity and sand concentration are high. The processes are complex and for this reason the development of predictive models relies on laboratory experiments in which detailed measurements can be made under well controlled flow and sand conditions. The most useful laboratory results have come from large experimental facilities in which the flow and sand conditions are the same as full-scale, i.e. flows in the facilities have a typical period range of 4 to 12 s and sands used in the experiments have a typical size range of 0.1 to 0.5 mm. The combined experimental results cover a wide range of flow and sand conditions and, in addition to measurements of net sand transport rates for given wave and sand conditions, include measurements of detailed processes that can-
not yet be measured in the field. In this paper we present an overview of important results from these experiments, covering the ripple and sheet flow transport regimes, and we describe key processes which need to be accounted for in predictive models. An account is given of modeling approaches, especially recent development of semi-unsteady models used for practical applications, where the development is based on insights and data from the large-scale laboratory experiments.

2. Large-scale laboratory experiments

Full-scale laboratory studies of wave-driven sand transport are carried out in large wave flumes and oscillatory flow tunnels. In wave flumes, free-surface waves with periods in the range 4 to 15 s and heights up to 2.5 m are generated in a long flume, traveling over a sand bed as they propagate from the wave paddle to a dissipating beach at the flume end. Examples of such flumes include the 230 m long Delta Flume of Delft Hydraulics in The Netherlands and the 300 m long GWK of the University of Hannover and the Technical University of Braunschweig in Germany. In flow tunnels, oscillatory flow is generated over a sand bed by piston motion within an enclosed tunnel. For the larger tunnels, the range of flow periods is typically 3 to 15 s and the amplitude of water motion within the tunnel test section can reach approximately 2 m. Oscillatory flow in the test section corresponds therefore to near-bed flow generated by large, non-breaking full-scale waves in a range of shoaling water depths. Examples of large tunnels include the Aberdeen Oscillatory Flow Tunnel (AOFT, Fig. 1) at Aberdeen University (O’Donoghue and Clubb 2001) and the Large Oscillating Water Tunnel (LOWT) at Delft Hydraulics in the Netherlands (Ribberink and Al-Salem 1994).

Fig. 1. The Aberdeen Oscillatory Flow Tunnel (AOFT). The tunnel is 16 m long with a glass-sided test-section that is 10 m long, 0.3 m wide and 0.75 m high.

Schretlen and van der Werf (2006) compiled a database of results from large-scale laboratory experiments on sand transport processes. The database contains results from approximately 750 experiments, the majority conducted in the LOWT, AOFT and the Tokyo University water tunnel. The most detailed experiments, involving measurements of fundamental processes, have been carried out in the LOWT and AOFT. By far the majority of these experiments involved wave-only conditions with sinusoidal or velocity-skewed oscillatory flows. The latter are defined by
\[ u(t) = u_i \sin \omega t - u_z \cos 2\omega t \]  

where: \( \omega = 2\pi/T \), \( T \) being flow period. The degree of skewness, \( R \), is

\[ R = \frac{u_i + u_z}{2u_i} = \frac{u_{\text{max}}}{u_{\text{max}} - u_{\text{min}}} \]

where: \( u_{\text{max}}, u_{\text{min}} \) = maximum positive, negative velocity (Fig. 2).

Fig. 2. Velocity-skewed flow used in many oscillatory flow tunnel experiments (\( R = 0.63 \) in example shown). Note higher ‘onshore’, positive velocity and longer-duration ‘offshore’, negative velocity.

3. Experimental results

3.1 Sand transport regime

For a given sand size and flow period, vortex ripples form as the amplitude of wave-induced flow velocity increases beyond the threshold velocity for sediment motion. As the flow amplitude increases, ripples increase in size, reach a maximum and then decrease in size at higher velocities. For sufficiently high velocity, the ripples are washed out completely and sand transport takes place within a thin, high concentration layer of sand over an essentially flat bed. This is the so-called sheet flow condition. Because the sand transport processes are very different between the ripple and sheet flow regimes, it is important to be able to predict which regime will occur for given wave and sand conditions.

O’Donoghue et al. (2006) looked at reported bed type from a wide range of large-scale laboratory tunnel and wave flume experiments. Classifying the beds as 3-d rippled, 2-d rippled, bimodal or flat (3D, 2D, BM or FB, Fig. 3), they found that bed type is reasonably well characterised by mobility number based on the high velocities in the flow, i.e. by

\[ \psi_{\text{max}} = \frac{u_{\text{max}}^2}{(s-1)gD_{50}} \]

for regular flows, and by

\[ \psi_{\text{off}} = \frac{u_{\text{off}}^2}{(s-1)gD_{50}} \]
for irregular flows, where: \( u_{1/10} \) = mean of highest one tenth velocities in the irregular velocity time-series; \( s \) = sediment specific gravity (2.65 for sand); \( g \) = acceleration due to gravity; \( D_{50} \) is the sediment size for which 50\% of the sediment sample is finer. Ripple regime occurs for \( \psi_{\text{max}}, \psi_{1/10} \leq 190 \) and sheet-flow for \( \psi_{\text{max}}, \psi_{1/10} \geq 300 \). In the transition regime, \( 190 < \psi_{\text{max}}, \psi_{1/10} < 300 \), it seems that the bed type is sensitive to the detailed experimental conditions and a variety of bedforms have been observed to occur. Within the ripple regime, ripples may be 2-d or 3-d and it is clear that mobility number does not determine which type occurs. Sand size is the primary factor determining whether ripples will be 3-d or 2-d in full-scale oscillatory flows, with 3-d ripples occurring when the sand is fine (<~0.2 mm) and 2-d ripples occurring when the sand is relatively coarse (>~0.3 mm).

### 3.2 Ripple dimensions

The dimensions of ripples play a crucial role in determining net sand transport in the ripple regime. Indeed, ripple height is often an explicit parameter in wave-driven sand transport models. A substantial body of field- and laboratory-based research has been devoted to measuring ripples and developing predictive formulae for ripple dimensions. Commonly-used formulae include those of Mogridge et al. (1994), Nielsen (1981) and Wiberg and Harris (1994). O’Donoghue et al. (2006) tested these formulae against a large set of full-scale tunnel and wave flume laboratory data. By focusing on full-scale laboratory experiments, they avoid the scale effects associated with small-scale experiments and the uncertainties associated with bed history effects and measurement difficulties in the field. Ripple dimensions predicted using Wiberg and Harris (1994) were found to be in poor agreement with the data; predictions based on Mogridge et al. (1994) and Nielsen (1981) are in better agreement, especially for ripple length, but both methods over-estimate the dimensions of 3-d ripples and Nielsen under-estimates ripple dimensions at high mobility and in irregular flows.
O’Donoghue et al. (2006) proposed modifications to the Nielsen equations, based on the extensive dataset of large-scale experimental data. For ripple height, $\eta$:

$$\frac{\eta}{a_{1D}} = 0.275 - 0.022\psi^{0.42} \quad \text{and} \quad \frac{\eta}{a_{2D}} = 0.55\frac{\eta}{a_{1D}}$$ (5)

where for regular flow: $a = \frac{d_o}{2}$, $\psi = \psi_{max}$; for irregular flow: $a = \frac{T_p u_{rms}}{\sqrt{2\pi}}$, $\psi = \psi_{1/10}$; $d_o =$ flow orbital diameter for regular flow; $T_p =$ spectral peak period; $u_{rms} =$ rms velocity. For ripple length, $\lambda$:

$$\frac{\lambda}{a_{1D}} = 1.97 - 0.44\psi^{0.21} \quad \text{and} \quad \frac{\lambda}{a_{2D}} = 0.73\frac{\lambda}{a_{1D}}$$ (6)

The equations apply for $10 \leq \psi_{max}, \psi_{1/10} \leq 190$. Figure 4 shows the comparison between the measured ripple dimensions and calculated dimensions using Nielsen and using equations (5) and (6).

Fig. 4. Predicted versus measured ripple dimensions for a wide range of full-scale laboratory conditions. Top panels: predictions based on Nielsen (1983). Bottom panels: predictions based on modified Nielsen equations as proposed by O’Donoghue et al. (2006). Different symbols correspond to different flow type (regular, irregular) and ripple type (2-d, 3-d).
Equations 5 and 6 apply to equilibrium ripple conditions. Transient ripples, i.e. ripples that are evolving in response to a change in wave conditions, are also of practical interest. Few detailed studies have been carried out on transient ripple behaviour. Smith and Sleath (2005), Davis et al. (2004) and Testik et al. (2005) studied transient ripples at small scale. Doucette and O’Donoghue (2006) studied transient ripples at large scale in the AOFT and proposed a simple exponential model for ripple evolution, with initial ripple height, equilibrium ripple height and mobility number as input, but calibration of their model is based on experiments involving one sand size only.

3.3 Ripple regime processes

Consider the case of ripples in regular, velocity-skewed flow, in which the onshore velocity maximum is greater than the offshore velocity maximum (Fig. 2). For this flow the ripples are asymmetric with steeper onshore (lee) than offshore (stoss) slopes. During onshore flow, the high onshore velocities transport a large volume of sand up the stoss slope and over the ripple crest. Some of this sand is entrained in the vortex that develops in the lee side. The vortex also entrains sand directly from the lee slope. The lee vortex becomes large as the flow slows, entraining more sand as it does so and is ejected into the main flow above the ripple at about the time of on-offshore main flow reversal, making a relatively large contribution to the offshore-directed suspended sediment transport. Some of the sand that was carried up the stoss slope and over the ripple crest during onshore flow does not get carried into suspension by the lee side vortex. Instead it slumps down the lee side contributing to onshore shift of the ripple position, i.e. it contributes to onshore ripple migration. The same processes occur during the offshore half cycle but, because of lower offshore velocities and a less steep stoss slope, (1) a weaker vortex is produced resulting in less onshore-directed suspended sediment transport and (2) much less sediment is carried up the steep onshore side and over the ripple crest resulting in less offshore ripple migration compared to onshore migration. For velocity-skewed flow, therefore, the net suspended transport is offshore-directed while net ripple migration is onshore; the total net transport depends on the relative magnitudes of the two contributions. Which contribution dominates depends on the ripple geometry, the flow and the sediment characteristics.

Many laboratory studies have been carried out to obtain quantitative measures of the flow and suspended sand dynamics, but these have generally been limited either by the capability of the available instrumentation or by the experiment scale or setup. Velocity measurements over fixed rippled beds have been conducted by Sato (1987), Earnshaw and Greated (1998), Doering and Baryla (2002) and Marin (2004), while Ahmed and Sato (2001) measured velocities over mobile sand ripples but their ripples were small. Sand concentrations have been measured by a number of researchers for full-scale laboratory conditions – Clubb (2001), Villard et al. (2000), Vincent and Hanes (2002), Thorne et al. (2003) – but no corresponding velocity measurements were made. van der Werf et al. (2007a) recently conducted experiments measuring the detailed time-varying velocity and suspended sand concentration fields over full-scale, mobile ripples in the AOFT, using particle image velocimetry (PIV) for the velocities and an acoustic backscatter system (ABS) for the concentrations. Their measurements
show the detailed dynamics of the vortices, the suspended sand and the sand flux (example measurements for the velocity field are shown in Fig. 5), all of which are dominated by the generation and ejection of vortices from the ripple sides at around times of flow reversal.

Fig. 5. Velocity field over ripple at 8 phases of a velocity-skewed flow (van der Werf et al. 2007a). Top panel shows free-stream velocity and the phases for the velocity field plots.

The time-averaged flows measured by van der Werf et al. (2007a) show a net offshore-directed current (streaming) within about one ripple height above the ripple crests. The streaming is generated by asymmetry in vortex generation from the ripple sides for the velocity-skewed flows, and increases as the degree of skewness increases.
The magnitude of the streaming is low (less than 10% of maximum free-stream velocity for flows with high skewness) but is important because it contributes a “current-related” flux to the net transport: for the van der Werf et al. experiment, the current-related flux contributes ~30% to the total suspended net transport.

Ribberink et al. (submitted) argue that the relative dominance of offshore-directed suspended transport and onshore-directed bedload transport (ripple migration) for velocity-skewed flow depends on a ripple regime “phase lag parameter”, \( p_r \), given by

\[
p_r = \frac{\eta \omega}{w_s}
\]

where: \( w_s \) = sand fall velocity. The greater the value of \( p_r \) (higher ripples/finer sand/shorter flow period), the stronger the phase lag effect and, for velocity-skewed flow, the greater the tendency towards suspension-dominated, offshore-directed net sand transport. Based on results from experiments conducted in the AOF and LOWT, they show that net transport is bedload-dominated, onshore-directed when \( p_r \geq 0.8 \) and suspension-dominated, offshore-directed for \( p_r < 0.8 \).

Fig. 6. CCM-measured time-series of sheet flow concentration at \( z = -4 \) mm to \( z = 2 \) mm for 0.27 mm sand in velocity-skewed flow (top left) (O'Donoghue and Wright, (2004a)).

3.4 Sheet flow processes
Sheet flow conditions prevail when the wave-generated bed shear stress is high and the sand transport takes place within a “sheet flow layer” consisting of a water-sediment mix moving over a flat, ripple-free bed. Detailed measurements of velocities and concentrations within the sheet flow layer provide insights and data for the devel-
development of models. The most detailed measurements have come from experiments carried out in recent years in the AOFT and LOWT, involving measurements of sheet flow concentrations and, to a lesser degree, sheet flow velocities. Figure 6 shows example sheet flow concentration measurements made by O’Donoghue and Wright (2004a) in the AOFT using concentration conductivity probes (CCMs) for a 0.27 mm sand in a velocity-skewed flow with $T = 7$ s and $u_{\text{max}} = 1.5$ m/s. Time-series of concentration are shown for $z$ positions ranging $-4 \leq z \leq 2$ mm, where $z = 0$ corresponds to the no-flow bed level.

Two regions can be identified within the sheet flow layer: (1) the “inner” or “pick-up” layer where concentration decreases at times of high velocity as sand is picked up and increases at times of low velocity as sand settles back to the bed; (2) the upper sheet flow layer where concentration increases around times of high velocity as sand is carried up from the pick-up layer. At some $z$ between the pick-up layer and the upper sheet flow layer (between $-1$ and $+1$ mm for the O’Donoghue and Wright experiments) the concentration stays reasonably constant with time.

![Figure 6](image1.png)

**Figure 6.** Example sheet flow concentration measurements made by O’Donoghue and Wright (2004a) in the AOFT using concentration conductivity probes (CCMs) for a 0.27 mm sand in a velocity-skewed flow with $T = 7$ s and $u_{\text{max}} = 1.5$ m/s. Time-series of concentration are shown for $z$ positions ranging $-4 \leq z \leq 2$ mm, where $z = 0$ corresponds to the no-flow bed level.

Example instantaneous concentration profiles from O’Donoghue and Wright (2004a) are shown in Fig. 7. They found that the profile within the sheet flow layer is well characterised by

$$
\bar{C} = \frac{1}{1 + \left( \frac{1}{C_0} - 1 \right) \left( \frac{z}{\delta_z} + 1 \right)^\alpha}
$$

![Figure 7](image2.png)

**Figure 7.** Example CCM-measured concentration profiles for 4 sands at time of maximum onshore (positive) velocity of a velocity-skewed flow (O’Donoghue & Wright, 2004a). Circles are data, solid line is fit of equation (8) to the data. $C_b$ is concentration in undisturbed bed.
where: $\bar{c} =$ concentration normalised by the undisturbed bed concentration; $\bar{c}_0 =$ normalized concentration at $z = 0$; $\delta_e =$ instantaneous erosion depth; $\alpha \approx 1.5$. If all of the mobilised sand is contained in the sheet flow layer (which is close to true for relatively coarse sand but not so for fine sand) then $\bar{c}_0$ in Eq. (8) is determined by the value of $\delta_e$ because the integrated concentration profile must then equal the eroded volume of sediment. $\delta_e$ itself depends on the flow and sand conditions. For relatively coarse sands, the erosion depth behaves in a near quasi-steady way, i.e. it is determined by the instantaneous bed shear stress:

$$\frac{\delta_e(t)}{D_{50}} = \phi(\theta(t))$$  \hspace{1cm} (9)$$

where $\theta(t)$ is the instantaneous Shields parameter:

$$\theta(t) = \frac{\tau(t)}{(s-1)\rho g D_{50}}$$  \hspace{1cm} (10)$$

with: $\tau =$ bed shear stress; $s =$ sand specific gravity (~2.65). However, for relatively fine sand with low settling velocity, sand that is entrained by high velocities is slow to settle back to the bed as the velocity decreases to zero and a proportion of the sand remains in suspension for transport in the opposite direction when the flow reverses. In such cases, $\delta_e$ depends on flow history as well as $\theta(t)$. This unsteady behaviour is seen in the case of fine sand in the example erosion depth and sheet flow layer thickness time-series shown in Fig. 8.

Dohmen-Janssen et al. (2001) argue that the degree of unsteadiness depends on the sand settling velocity, the flow period and the sheet flow layer thickness: they characterise the degree of unsteadiness by (2$\pi$ times) the ratio of the time taken for a sand grain to settle through the sheet flow layer to the flow period, i.e.,

$$p_s = \frac{\delta_s \omega}{w_s}$$  \hspace{1cm} (11)$$

where: $\delta_s$ is the thickness of the sheet flow layer defined as the distance from the (maximum) erosion depth to the elevation where the volumetric concentration is 8%. Unsteady effects become increasingly important for increasing $p_s$ (finer sand, shorter flow periods, thicker sheet flow layer). Ribberink et al. (submitted) show that for $p_s > 0.3$ the degree of unsteadiness is such that for velocity-skewed flows the net sand transport direction is negative, i.e. opposite to the direction of the higher velocities.

Velocity measurements within the sheet flow layer are difficult because of the presence of high sand concentrations. O’Donoghue and Wright (2004b) used an ultrasonic velocity profiler (UVP) to measure sheet flow velocities and report measurements reaching quite far into the sheet flow layer (as far as the $z = 0$ level). Combining their velocity and concentration measurements, they obtained measures of the vertical profiles of the time-varying sand flux. For coarse sand in velocity-skewed flow (Fig. 2), unsteady effects are negligible, the bed responds in a quasi-steady way, sand flux is
confined to a narrow layer close to \( z = 0 \) and the net sand transport is positive. In contrast, for fine sand the bed behaves in an unsteady manner, the sand flux extends relatively high above the bed and net transport in the sheet flow layer is strongly negative in velocity-skewed flow.

As for flow over ripples, the time-averaged velocity profiles for velocity-skewed flows show an offshore-directed near-bed streaming with magnitude of order 10% of maximum free-stream velocity. For this flat-bed case the streaming is caused by the asymmetry in the turbulent stresses between the two halfcycles of the flow. As for rippled beds, associated with the streaming is a current-related net sand flux, but in the case of sheet flow the current-related flux can be greater than the wave-related flux (Ribberink et al., submitted). This means that differences between near-bed streaming in tunnels and near-bed streaming under real waves could be very significant. Indeed, Dohmen-Janssen and Hanes (2002) concluded, from a set of experiments conducted in the full-scale GWK wave flume in Hannover, that sheet flow net sand transport rates under real waves may be up to 2.5 times greater than the transport rates in “equivalent” tunnel oscillatory flow and they attribute the difference to differences in the near-bed streaming.
3.5 Net sand transport

Of the approximately 750 experiments listed by Schretlen and van der Werf (2006), almost 500 involved measurement of net sand transport rate. A subset of the results is presented in Fig. 9. It shows measured net sand transport rate, \( q_s \), plotted against mobility number, \( \psi \), for AOFT and LOWT experiments with velocity-skewed regular oscillatory flow. The data cover a sediment size range of 0.13-0.46 mm and a flow period range of 3.1 to 12.5 s. Three groups of results are shown. The first group comprises results from the ripple regime (circles), for which, with a few exceptions, the net sediment transport is in the offshore (negative) direction. For these cases, the phase lag parameter is relatively high, the transport is suspension-dominated and the flow asymmetry leads to the offshore net sand transport. The second group comprises results for medium and coarse sands \((D_{50} > 0.2 \text{ mm})\) in the sheet flow regime (triangles). Net transport for this group is onshore (positive) and generally increasing as \( \psi \) increases. These results correspond to conditions where the sheet flow phase lag parameter \( \rho_s < 0.3 \) and the bed response and sand flux behave in a quasi-steady manner with the instantaneous flux being a function of the instantaneous bed shear stress. The third group comprises results corresponding to fine sands \((D_{50} \leq 0.2 \text{ mm})\) in the sheet flow regime (squares). These results show a positive onshore net transport at first but then an increasing negative net transport as \( \psi \) increases. For these cases of fine sand, unsteady effects become increasingly dominant with increasing \( \psi \). The greater the unsteady effect, the more sand remains in suspension at the end of the high velocity onshore half-cycle, which is then available for transport in the offshore direction during the lower velocity offshore half-cycle.

![Fig. 9. Measured net transport rates from LOWT and AOFT experiments with regular, velocity-skewed oscillatory flows.](image-url)
4. Modelling wave-driven sand transport

Models for wave-driven sand transport range from relatively simple “practical” models based on empirical formulae to “process” models which aim to explicitly model the detailed intra-wave processes. The full-scale laboratory data previously discussed are used to test and develop both types of model.

4.1 Process Models

Process models vary widely in their degree of complexity. For sheet flow, process models range from 1DV advection-diffusion boundary layer models (e.g. Ribberink and Al-Salem 1995, Davies and Li 1997, Dohmen-Janssen et al. 2001), which solve the momentum equation for the flow and the diffusion equation for the suspended sediment concentration, to more complex two-phase models which model the full diffusive and collisional processes within the sheet flow layer (e.g. Dong and Zhang 1999, Hsu et al. 2004, Liu and Sato 2006). The advection-diffusion models use an empirical reference concentration formula near the bed and do not model the sheet flow layer. A practical compromise between the advection-diffusion and the two-phase models is to couple a simple model of the essential sheet flow processes with an advection-diffusion model higher up (e.g. Kaczmarek and Ostrowski 2002, Malarkey et al. 2003).

For the ripple regime, a 2DV modeling approach is needed to properly capture the vortex shedding process. Ripple regime process models include RANS models with various turbulence closure schemes (e.g. Eidsvik 2006) and discrete vortex models (e.g. Malarkey and Davies 2002). Since 2DV models are too complex for practical application, Davies and Thorne (2005) proposed a simple 1DV two-layer model, in which vortex shedding in the lower layer is represented by a time-varying eddy viscosity, and a standard turbulence-closure formulation is used for the upper layer. As for the sheet flow RANS models, the ripple models require an empirical reference concentration or sand pickup function.

4.2 Practical Models

Formula-based models are used for practical applications of sand transport calculations in the coastal zone. There are two main classes of model: (1) quasi-steady models in which the instantaneous transport rate is directly related to some power of the instantaneous bed shear stress or near bed flow velocity (e.g. Bailard 1981, van Rijn 1993, Ribberink 1998), and (2) semi-unsteady models which account for unsteady (phase lag) effects of the kind described above without modeling the detailed time-dependent horizontal velocity and concentration vertical profiles (e.g. Dibajnia and Watanabe 1996, Dohmen-Janssen et al. 2002, Camenen and Larson 2006, da Silva et al. 2006, van der Werf et al. 2007b).

Considering the quasi-steady model of form

\[ \phi(t) = m |\theta(t)|^{\bar{\theta}(t)} \]

(13)
where $\phi(t) = \frac{q_0(t)}{\sqrt{(s-1)gD^3}}$ = non-dimensional transport rate, it can be shown that the net transport for a velocity-skewed oscillatory flow (equation 1) is

$$\phi_n = \alpha m \left[ \frac{a_m}{1 + (2R-1)^2} \right] \theta_{\text{q} \text{u} \text{m} \text{s}}$$

where $\phi_n = \frac{1}{T} \int_0^T \frac{q_0(t)}{\sqrt{(s-1)gD^3}} dt$; $\theta_{\text{q} \text{u} \text{m} \text{s}} = \frac{0.5 f_n (\sqrt{2}u_{\text{rms}})^2}{(s-1)gD}$; $\alpha$ depends on $n$ and the degree of skewness $R$. For $m = 11$, $n = 1.65$ (as per Ribberink 1998) and skewness $R = 0.63$, $\phi_N = 2.12 \theta_{\text{q} \text{u} \text{m} \text{s}}^{1.65}$. Quasi-steady models always predict a net onshore (positive) transport for velocity-skewed flow, increasing with increasing Shields parameter. Predictions agree reasonably well with measured transport rates for relatively coarse sand in sheet flow conditions (low $\rho_s$), but, because of unsteady phase lag effects, predictions are poor for ripple regime and sheet flow regime with relatively fine sand.

A number of semi-unsteady models have been proposed in recent years in an attempt to account for unsteady effects. Dohmen-Janssen et al. (2002) applied a phase lag correction factor (based on the lag parameter given by equation 11) to the quasi-steady model of Ribberink (1998). A number of other models are based on the “half-cycle approach” proposed by Dibajnia and Watanabe (1992, 1996, 1998). In this approach the quantity of sand transported in the onshore direction comprises (1) sand that is entrained and transported during the onshore half-cycle ($\Omega^c$, “c" for crest) and (2) sand that was entrained during the preceding offshore half-cycle but did not settle back to the bed by the end of the offshore half-cycle ($\Omega^t$, “t" for trough). Similarly, sand transported in the offshore direction comprises $\Omega^t$ and $\Omega^c$. The concept has been applied for sheet flow conditions by Dibajnia and Watanabe (1996), Camenen and Larson (2006) and da Silva et al. (2006), and for ripple regime by van der Werf et al. (2006). A unified model, i.e. covering both ripple and sheet flow regimes, waves and waves plus currents, has recently been proposed by van der Werf et al. (2007b), based on the dataset of large-scale laboratory data compiled by Schreitlen and van der Werf (2006).

In van der Werf et al. (2007b), the net sand transport is

$$\phi_n = \frac{mT}{T} \left( \Omega^c + \Omega^t \right) - \frac{mT}{T} \left( \Omega^t + \Omega^c \right)$$

where: $T =$ wave period; $T_c =$ wave crest duration (duration of onshore, positive velocity); $T_t =$ wave trough duration (duration of offshore, negative velocity); $m =$ calibration factor. The first term on the right hand side of Eq. (15) is the onshore transport with two contributions ($\Omega^c + \Omega^t$) and the second term is the offshore transport with two contributions ($\Omega^t + \Omega^c$). The magnitudes of the contributions within each half-cycle depend on the excess shear stress $(|\theta| - \theta_{\text{c}},)$ and the value of the phase lag pa-
rameter $p$ for the half-cycle, where for rippled bed $p = p_r = \frac{\eta}{T_i w_s}$ (Eq. 7) and for sheet flow $p = p_s = \frac{\delta}{T_i w_s}$ (Eq. 11), where $i = c$ or $t$ for crest or trough respectively and $\alpha_c$, $\alpha_s$ are calibration factors. Sub-models for bed shear stress, ripple size, sheet flow layer thickness are based on results from the large-scale experiments as described earlier in this paper.

Figure 10 shows predicted-versus-measured net sand transport rates using the van der Werf et al. (2007b) model. The model does better in the sheet flow regime than in the ripple regime. In sheet flow, predicted transport rates are generally within a factor two of measured transport rates and the model captures unsteady effects quite well, as evidenced by the reasonable agreement between the measured and predicted negative net transport rates. Agreement is not as good in the ripple regime: some very high measured negative transport rates are underpredicted and a number of cases of measured onshore transport are predicted as being offshore, although the transport magnitudes in the latter cases are mostly small. Good agreement in the ripple regime is more difficult to achieve because of limited predictability of ripple height (the model gives better agreement if measured ripple heights are used rather than predicted ripple heights) and because sand transport rates are often very low in the ripple regime.
5. Conclusions

Large-scale laboratory experiments have produced valuable data and insights used to develop process and practical models for sand transport under waves. The majority of the experiments have been conducted in oscillatory flow tunnels and mostly with velocity-skewed flows. For this reason knowledge of some fundamental questions is still somewhat lacking. Two questions in particular need further study. (1) The first concerns the difference between oscillatory flow in a tunnel and near-bed flow under real waves. Phase differences in wave orbital motion, vertical orbital motions, wave-induced boundary layer streaming (Longuet-Higgins 1953) and undertow at higher levels above the bed are not reproduced in flow tunnels. Of these, the wave-induced streaming is likely to be of most significance because although the magnitude of streaming is small compared to the orbital velocities, the streaming-related sand flux can be high, especially for sheet flow. (2) The second question concerns the effects of flow acceleration. Non-zero net transport rates have been measured in experiments with acceleration-skewed flow (sawtooth-type velocity time-series), with higher transport in the direction of higher flow acceleration (e.g. Watanabe and Sato 2004) caused by enhanced bed shear stress (Nielsen 2002). Models in which the bed shear stress is a function of free-stream velocity cannot account for the acceleration effect. More detailed large-scale experimental data are needed to improve understanding of acceleration effects and to test recent suggestions (e.g. da Silva et al. 2006, Rodriguez and Madsen 2007) for incorporating acceleration effects in practical models. Both these issues – real wave and acceleration effects – are being studied as part of a current UK-Dutch collaborative research project (SANTOSS).

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