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THE ROLE OF STEADY STREAMING IN SHEETFLOW TRANSPORT

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To quantitatively evaluate the role of the onshore streaming, laboratory experiments were conducted under the combined asymmetric wave-current conditions. The asymmetric flows with a wave period of 5 s and a maximum onshore velocity u_{max} varying from 0.8 to 1.6 m/s have been applied for three well-sorted sands with different medium sand sizes. The sediment net transport rate was measured. Results show that except several cases, the onshore streaming enhanced the onshore sheetflow net transport by different extents. The streaming-induced net transport rate is found to be related to the free-stream velocity and the sand size.

1. Introduction

Many coastal activities are concerned with the interaction of coastal sedimentary processes and coastal works, such as the construction of structures for shore protection and stabilization, and beach nourishment. It is important to measure sand properties, sediment moving processes and transport rates, as well as the resulted nearshore morphology to understand the sediment transport mechanism under various wave and current conditions.

Recently, it is found that under the sheetflow condition, sediment net transport rate measured through the large wave flume (LWF) experiments presents a more onshore tendency, *i.e.*, a larger onshore net transport, than the result from the small oscillatory flow tunnel (OFT) experiments [1-2]. Various researchers argue that the wave-induced onshore streaming could be the reason to cause such difference between the LWF and OFT experiment results since such onshore streaming only occurs under the LWF condition under which the water particle vertical movement is not suppressed as it is under the OFT condition. This steady streaming velocity in the bottom boundary layer was firstly proposed by Longuet-Higgins [3-4]. The horizontal and vertical velocities in a wave motion are not exactly 90 degrees out of phase which gives rise to a non-zero time-averaged near-bed Eulerian drift, named as a streaming, which is a wave-induced near-bed steady current. To assess the effect from a boundary streaming to the net sediment transport, several studies have been performed through experiments and numerical simulations [5-8]. However, the real insight into this problem is still unclear. Therefore, sophisticated experimental studies are required to understand the physical feature of this phenomenon and answer the question: Does onshore streaming really enhance the onshore sheetflow net sand transport? If not, then, what is the real reason behind? If so, then, how and how much does it affect the onshore transport? To meet this objective, a series of experiments was conducted in the OFT at the University of Tokyo.

2. Methodology

2.1. *Oscillatory Flow Tunnel*

A schematic diagram of the Oscillatory Flow Tunnel (OFT) used in this study and its dimensions are shown in Fig. 1. The OFT consists of a loop of closed conduits and a driven piston. The tunnel is equipped with a 5.7 m long rectangular horizontal test section with a height of 24 cm and a width of 7 cm. A 40 mm deep flat sand bed is situated at the central of the test section with mild slopes at both ends. Sands are filled into the test section resulting an initially flat bed. The test section is surrounded by a glass sidewall on the observational side, a black painted wooden board on the opposite side and detachable ceilings. Sand traps made of honeycombs are installed at both ends of the test section in order to collect the sand that is transported away from the test section. In addition, an onshore or offshore steady current superposed with the oscillatory flow is generated by a circulation system which is controlled by a pump. Two discharge meters are installed on both sides of the current circulation section. The current velocity U_c inside the test section can be calculated,

$$U_c = \frac{Q}{bh} \tag{1}$$

where Q is the discharge rate, b and h are the width and height of the test section, respectively.

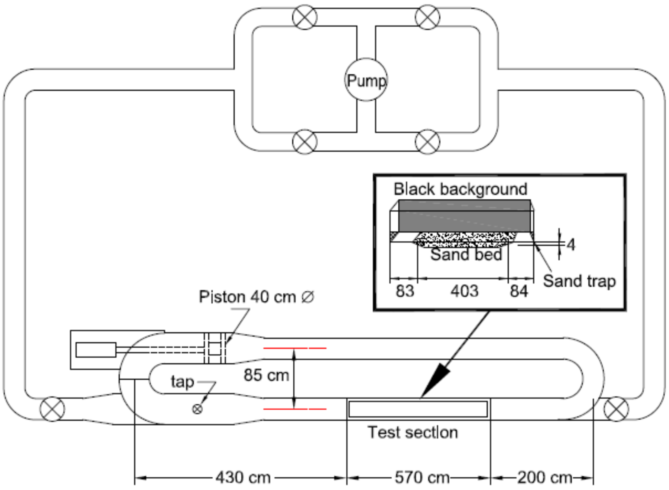

Figure 1. Schematic diagram of the oscillatory flow tunnel at the University of Tokyo (inset is a close-up view of the test section)

2.2. *Experimental Set-up*

To quantitatively evaluate the influence of the onshore streaming to the sheetflow sand transport, laboratory experiments were conducted under the asymmetric wave and current conditions, and the corresponding net sand transport rate was recorded. Onshore streaming velocity for the 2nd-order Strokes' wave theory can be estimated by [3],

$$U_c = \frac{3}{4c}\left(\frac{a\omega}{\sinh(kh)}\right)^2 \tag{2}$$

where a is the wave amplitude, ω is the angular frequency, k is the wave number, h and c are the wave height and wave celerity, respectively. In this study, the assumed water depth and wave height are 3.5 m and 1.2 m based on the wave flume data [2].

In the present experimental study, asymmetric flows with a wave period of 5 s and a maximum onshore velocity $u_{\max}$ varying from 0.8 to 1.6 m/s were applied to three well-sorted sands with a medium sand size of D_{50}= 0.13 mm (very fine), 0.16 mm (fine) and 0.3 mm (coarse). To understand the effect of onshore streaming, a small onshore steady current U_c of 10 cm/s which is calculated based on Eq. 2 was superimposed in the same direction with wave propagation, *i.e.*, the onshore direction. Sheetflow transport regime was confirmed for all experimental conditions. A velocity asymmetric index R_v=0.57 was used, which is defined as,

$$R_v = u_c / (u_c + u_t) \tag{3}$$

Where u_c and u_t are crest velocity and trough velocity, respectively. Experimental conditions and results for all tests are tabulated in Table 1. In total, 24 cases were carried out with asymmetric waves and combined asymmetric wave and current conditions. For very fine and fine sand cases, the net transport rate was determined by averaging the results of 2 or 3 tests. For coarse sand cases, the measurement of net rate was not repeated and only one time measurement is made because the error due to the sand loss is small.

Table 1.Experimental conditions for all laboratory tests

Test	T (s)	D_{50} (mm)	u_{max} (m/s)	q_{net} (cm^2/s)		q_{net} (cm^2/s)	
				U_c=0 (cm/s)	Error (-)	U_c=10 (cm/s)	Error (-)
T5VF1	5	0.13	0.8	-0.17	0.3	-0.12	0.5
T5VF2	5	0.13	0.9	-0.35	0.2	-0.25	0.4
T5VF3	5	0.13	1.0	-0.35	0.2	-0.53	0.3
T5VF4	5	0.13	1.2	-0.83	0.1	-0.63	0.3
T5F1	5	0.16	0.8	0.05	-0.3	0.28	-0.1
T5F2	5	0.16	1.0	0.09	-0.4	0.38	-0.2
T5F3	5	0.16	1.2	-0.18	0.2	0.37	0.2
T5F4	5	0.16	1.4	-0.44	0.1	-0.55	0.3
T5F5	5	0.16	1.6	-0.93	0.1	-0.83	0.3
T5C1	5	0.3	1.2	0.27	-0.03	1.22	-0.01
T5C2	5	0.3	1.4	0.55	-0.02	1.6	-0.01
T5C3	5	0.3	1.6	0.8	-0.02	1.56	-0.02

2.3. *Experimental Measurement*

In experiments, a wooden plate was initially placed in the middle of the test section to separate onshore and offshore parts. Then, the dry sand was placed at each side and assured an initially flat bed. After operating the experiment, sands remained at each part and stored inside sand traps were taken out carefully. Subsequently, each part of sands was placed in an oven to dry completely for 24 hours. Finally, the dried sand was weighted and the net transport rates were calculated based on the mass difference between the two parts after a recorded experimental duration Δt_{exp} by [9],

$$q_{meas} = \frac{\Delta M_{on} - \Delta M_{off}}{2b\rho_s \Delta t_{\mathrm{exp}}} \tag{4}$$

where q_{meas} is the measured net sand transport rate, ΔM_{on} and ΔM_{off} are the sand mass difference of the onshore and offshore parts before and after experiment, respectively. b is the width of the tunnel, and ρ_s is the sediment density. The experimental error is estimated through [9],

$$error = \frac{\Delta M_{on} + \Delta M_{off}}{\Delta M_{on} - \Delta M_{off}} \tag{5}$$

3. Results and Discussions

3.1. *Influence of Steady Streaming*

Measured net transport rates for all 24 cases are summarized and illustrated in Fig. 2. Without onshore streaming, the net sand transport with respect to the free-stream velocity under the sheetflow condition shows the similar trend with previous studies [8-10]. For very fine sand, net sand transport goes to offshore direction even under the small velocity, and its magnitude increases with the increasing velocity. For fine sand under the small velocity condition, net transport rate presents a rather small value in the onshore direction, and it changes to the offshore direction with the increasing wave velocity. Considering the coarse sand, the net transport is in the onshore direction.

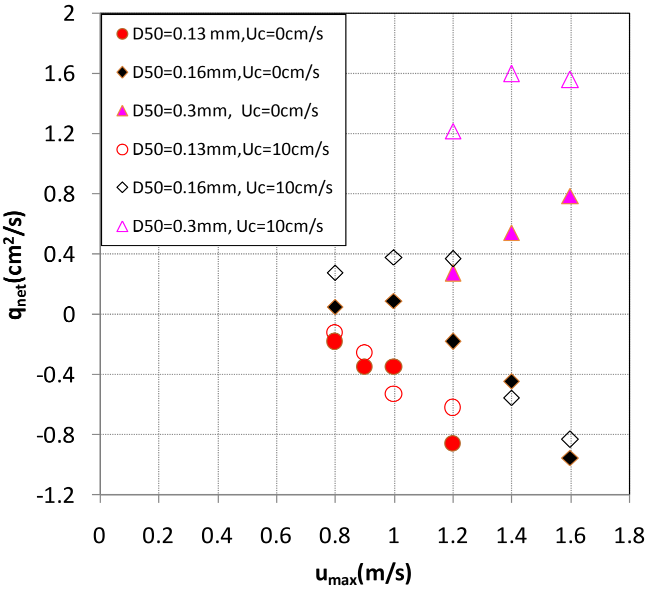

Figure 2. Comparison of the measured net transport rate for cases with and without current.

Taking into account the net transport rate measured under the combined wave and current cases, for most cases, onshore steady streaming enhances the onshore sand transport (solid marks to empty marks). For instance, magnitude of the offshore net transport reduces for the very fine sand case, and the onshore net transport for coarse sand case increases. Hereafter, such difference on the net sand transport rate owing to the steady streaming is referred to as the streaming-induced net transport rate. A positive value of such net transport rate corresponds to an enhancement of the net sand trasport in the onshore direciton.

3.2. *Streaming-induced Net Transport Rate*

Dohmen-Janssen *et al.* [8] suggested the phase-lag effect in the sheetflow transport regime which enhances the offshore sand movement. The phase-lag effect becomes significant under the condition of small sand size, short wave period and large free-stream velocity. As aforementioned, the onshore streaming, in general, supports the onshore sand movement. Therefore, investigation on the sediment transpot under the combined wave-current flow conditions can be regarded as an interaction between these two factors, the wave factor and the current factor. Figure 3 illustrates the relationship between the streaming-induced net trasport rate and the free-stream velocity. Taking into account the effect of sand size, it is confirmed that under the same velocity condition, streaming-induced onshore net transport is the most significant in case of the coarse sand for which the phase-lag effect prone to offshore movement is minimum. Whereas, fine sand with a large phase-lag effect demonstrates a small increase on the net transport rate.

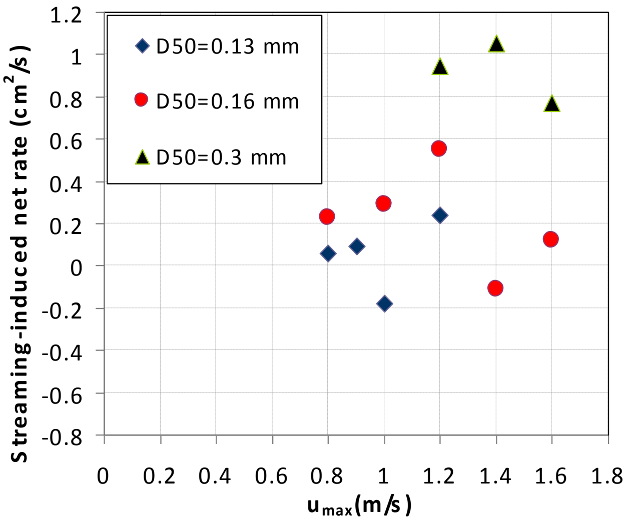

Figure 3. Relation between streaming-induced net transport rate and flow velocity.

On the other hand and for the same sized sand, increase of the onshore net transport rate due to boundary streaming is related to the free-stream velocity in a fairly complex pattern. When the free-stream velocity is small, increasing velocity enhances the onshore net trasport under which the boundary streaming plays a more important role on the sand movement since the phase-lag effect is insignificant for such small velocity cases. Whereas, for a larger velocity, *e.g.*, >0.9 m/s for very fine sand, >1.2 m/s for fine sand and >1.4 m/s for coarse sand, enhancement on the onshore net transport rate decreases. In case of u_{max}=1.0 m/s for very fine sand and u_{max}=1.4 m/s for fine sand, a small onshore streaming even enhances the offshore sand transpot (negative values in Fig. 3). Under such large velocity condtion, the phase-lag effect leading to an offshore net transport becomes crucial. Onshore transport due to a small streaming current could not overturn such trend from the phase-lag effect. In another words, the wave factor is more important than the current factor in these cases. As a result, increase on net sand transport owing to the boundary streaming tails off for the large velocity cases. However, further increasing the velocity for these two cases, the streaming-induced net transport rate returns back to the onshore direction which indicates influence from the streaming becomes predominant.

As a result, steady onshore boundary streaming, in general, supports the onshore sheetflow transport. However, for small sand cases, it leads to a complex and sensitive features that enhancement on the offshore transport owing to the significant phase-lag effect may occur under certain velocity conditions. Further investigation is needed to scrutinize this phenomenon.

4. Conclusion

A series of experiments was performed in an oscillatory flow tunnel and measurements of the net transport rate were conducted under asymmetric waves superimposed with an onshore streaming. It is concluded that in general, the measured net transport rate with an onshore streaming results a larger onshore net transport comparing to that without streaming. Several exceptions were confirmed for fine sands under certain free-stream velocity conditions under which onshore streaming even enhances the offshore net transport, which is attributed to the phase-lag effect. The present experimental study shows the streaming-induced net transport rate is quantitatively affected by various factors, such as the free-stream velocity and the sand size.

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