Onshore sheetflow sand transport enhanced by small onshore currents superimposed to skewed velocities

KYIKYI LWIN[1], Haijiang LIU[1] and Shinji SATO[1]

Abstract: To answer the question whether the additional net onshore current contributes to a larger onshore net rate and to investigate the behavior of mean flow velocity profiles, a series of experiments was performed in the oscillatory flow tunnel and measurements of the net sand transport rate were conducted under asymmetric waves superimposed with an onshore current. The information of particle velocity at high concentration in the sheet flow was measured by means of PIV technique. 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, 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.

Keywords: sheetflow, onshore streaming, sediment transport, oscillatory flow tunnel, PIV

Introduction

General

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. A number of studies on the subject of sediment transport mechanisms under various wave and current conditions have been conducted using different approaches by former researchers. In this paper, we are interested in understanding the sediment transport mechanism, especially the influence of wave-induced boundary layer streaming on sediment transport under combined wave and current conditions in the sheetflow regime. The steady streaming velocity in the bottom boundary layer was firstly introduced by Longuet-Higgins (1957). The horizontal and vertical velocities in the wave boundary layer 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. It is a wave-induced weak near-bed steady current.

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 movement than that from Oscillatory Flow Tunnel (OFT). 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 develops only under the LWF condition under which the water particle vertical movement is not suppressed as it is under the OFT condition.

Objectives

To assess the effect of the boundary streaming to the sheetflow sediment transport, several studies have been conducted through experiments and numerical simulations, such as Dohmen-Janssen and Hanes (2002), Nielsen (2006) and Schretlen *et al.* (2010). However, the real insight into this problem is still unclear. Comprehensive 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 so, then, how and how much does it affect the onshore transport? In addition, in order to study the behavior of mean flow velocity profiles, detailed velocities measurement of the sediment particles and mean flow velocities profiles in the near bed boundary layer was investigated by applying PIV technique.

[1] Department of Civil Engineering, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Methodology

Oscillatory Flow Tunnel

In order to accomplish the objectives mentioned above and to answer the research questions, the experimental approach is adopted. A series of experiments was conducted in the OFT at the University of Tokyo. 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 hydraulically-driven piston. The tunnel is equipped with a 570 cm 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 center of the test section with mild slopes at both ends. Sands are filled into the test section forming 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 would be transported away from the test section. In addition, an onshore or offshore steady current superimposed 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.

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 according to Longuet-Higgins (1957),

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

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.

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

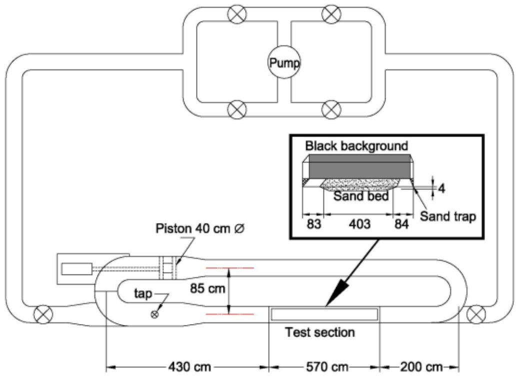

Fig. 1. Schematic diagram of the oscillatory flow tunnel (all dimensions are in cm)

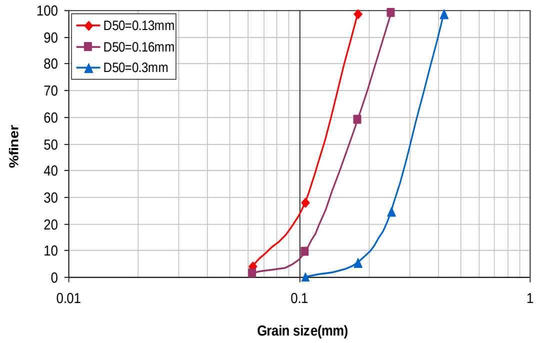

Fig. 2. Grain size distribution curves of the three sands in the experiments

medium sand size of D_{50}= 0.13 mm (very fine), 0.16 mm (fine) and 0.3 mm (coarse). The sieve analysis of these sands was provided in Fig. 2. To understand the effect of onshore streaming, a small onshore steady current U_c which is calculated based on Eq. 2 was superimposed in the same direction with wave propagation, *i.e.*, the onshore direction. 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 magnitudes, respectively. Experimental conditions and results for all tests are tabulated in Table 1. In total, 33 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. The movement of sediment processes is recorded by High Speed Video Camera. Temporal and spatial distributions of sediment particle velocities were investigated using Particle Image Velocimetry (PIV). To remove the noise influence in PIV analysis, a Fast Fourier Transform (FFT) algorithm was used to obtain the predominant velocity component, then average over one wave period to achieve the vertical profile of the mean flow velocity, $U(z)$.

Table1. Test conditions and measured net transport rates

Test	T (s)	D_{50} (mm)	u_{max} (m/s)	q_{net} (cm^2/s)		
				U_c=0 (cm/s)	U_c=10 (cm/s)	U_c=20 (cm/s)
VF1	5	0.13	0.8	-0.17	-0.12	0.27
VF2	5	0.13	0.9	-0.35	-0.25	0.28
VF3	5	0.13	1.0	-0.37	-0.35	-
VF4	5	0.13	1.2	-0.83	-0.63	-
F1	5	0.16	0.8	0.05	0.28	-
F2	5	0.16	1.0	0.09	0.38	0.41
F3	5	0.16	1.2	-0.18	0.31	0.56
F4	5	0.16	1.4	-0.57	-0.45	-0.25
F5	5	0.16	1.6	-0.93	-0.83	-0.6
C1	5	0.3	1.2	0.27	1.22	1.3
C2	5	0.3	1.4	0.55	1.56	1.6
C3	5	0.3	1.6	0.8	1.6	1.85

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 filled in each side and assured an initially flat bed. After operating the oscillatory flow, 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},

$$q_{meas} = \frac{\Delta M_{on} - \Delta M_{off}}{2b\rho_s \Delta t_{\exp}} \qquad (4)$$

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 was estimated through Ahmed and Sato (2001),

$$error = \frac{\Delta M_{on} + \Delta M_{off}}{\Delta M_{on} - \Delta M_{off}} \qquad (5)$$

The measuring procedures were performed by an enhanced PIV technique. The layout sketch of PIV experiment utilized for image analysis is shown in Fig. 3. By installing the HSVC (High Speed Video camera) very close to the glass sidewall, the experiments were conducted in OFT. Two light sources were adjusted so as to illuminate the tracers (fine sand). By putting a black background, only the sand particles became sources of light due to the reflection. The oscillations were generated to the

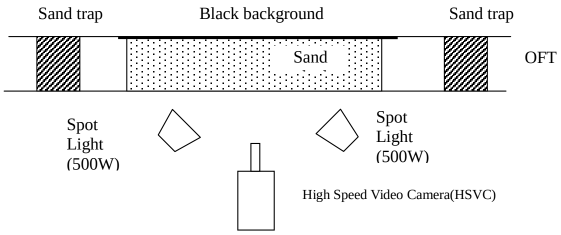

Fig. 3. Experimental apparatus utilized for image analysis (top view)

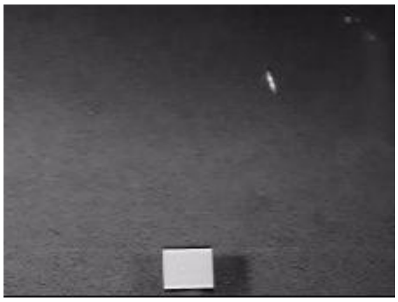

Fig.4. Typical visualized image

steady state before recording each case. (HSVC) produced 420 frames in one second and recorded the experimental processes. Using such images, we can perform the PIV technique to estimate the sediment particles velocity. Then, the video was transferred into PC and convert the video frames into bitmap images using computer software. The frames were captured up to 2100 bitmap files for wave period 5 s (420 frames x 5.0 s). The size of the frame was 220 by 168 pixels. In which, each pixel has the gray value or brightness value, in the range from 0 to 255. A typical visualized image utilized in the PIV technique including an image scale is shown in Fig.4. To calculate the image scale (pixels correspond to metric measure); a tape with known size (10mm x 8 mm) was glued at the area of interest.

Results and Discussions

Influence of Steady Streaming

In order to know the influence of oscillatory flow velocity and the contribution of onshore current on net transport, the net transport rate is plotted against the flow velocity for three different types of sand. Sheetflow transport regime was confirmed for all experimental conditions and the sediment net transport rate was measured. Fig. 5 shows the net sand transport rates for very fine sand case. The positive value represents the onshore sediment transport rate and negative one is the offshore net transport rate. The net sand transport goes to offshore direction even under the small velocity, and its magnitude increases with the increasing velocity. Taking into account the net transport rate measured under the combined wave and current cases, onshore steady streaming enhances the onshore sand transport. For instance, magnitude of the offshore net transport reduces for the very fine sand case with the onshore current U_c= 0.1 m/s. Further increasing the magnitude of onshore current to U_c = 0.2 m/s, the offshore net rate significantly decreases and its direction changes to onshore (empty marks to solid marks) in the case of very fine sand.

The measured net transport rates for fine sand are illustrated in Fig. 6. It indicates that, for fine sand concerning the small velocity condition, the net transport rate presents a rather small value in the onshore direction. For small velocity case (u_{max}= 0.8 m/s and 1.0 m/s) without onshore streaming, the net transport increases with increasing velocity, and it is directed to the onshore. However, for larger velocity case (u_{max} >1.0 m/s), the net transport rate decreases and the direction also changes to the offshore. In the case of combined wave and current, the onshore net rate is occurred with small velocity case. But, when the velocity further increases, even though the offshore net value reduces, the direction is still offshore. It can be explained that the phase-lag effect of very fine and fine sand in the sheetflow transport regime. The phase-lag effect enhances the offshore sand movement which becomes significant under the condition of small sand size, short wave period and large free-stream velocity (Dohmen-Janssen *et al.* 2002). As for the coarse sand without onshore streaming, the net transport rate continuously increases and is directed to the onshore when increasing flow velocities. It is because when the velocity is larger, the entrainment of sand into the flow is also stronger and sand has enough time to settle to the bed as the settling velocity is larger. So, the net sediment is transported to the onshore direction before the occurrence of negative velocity. And also, the bed load is dominant rather than suspension load in coarse sand. To understand the effect of onshore streaming, a small current of 0.1 m/s and 0.2 m/s was generated in the onshore direction. The experiment results show a larger onshore net transport rate compared to without streaming case. Even though we contribute the larger positive onshore current, the results between U_c = 0.1 and 0.2 m/s shows not too much significant difference for the flow velocity case of u_{max}=1.2 m/s and 1.4 m/s. It seems the effect of larger onshore streaming is not dominant in case of coarse sand.

As a result, steady onshore boundary streaming, in general, supports the onshore sheetflow transport. However, for small sand cases, the enhancement on the offshore transport owing to the significant phase-lag effect may occur under certain velocity conditions. It is concluded that in general, the measured net transport rates with an onshore streaming produce a larger onshore net transport compared to without streaming for all cases. Hereafter, such difference on the net sand

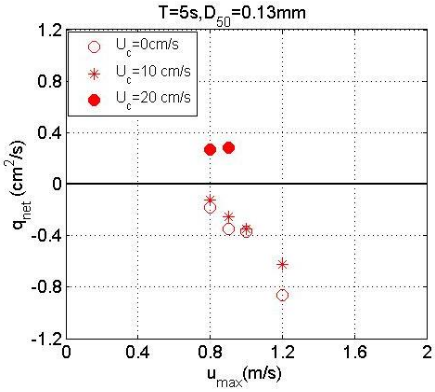

Fig.5. Net transport rate as a function of flow velocity for very fine sand

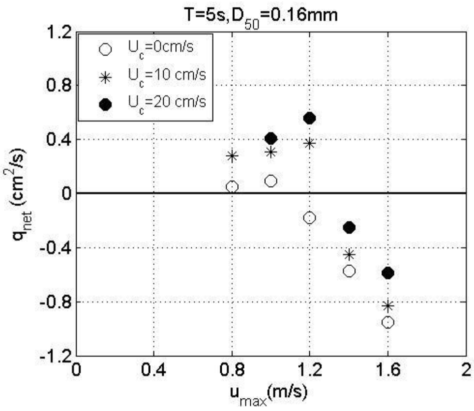

Fig. 6. Net transport rate as a function of flow velocity for fine sand

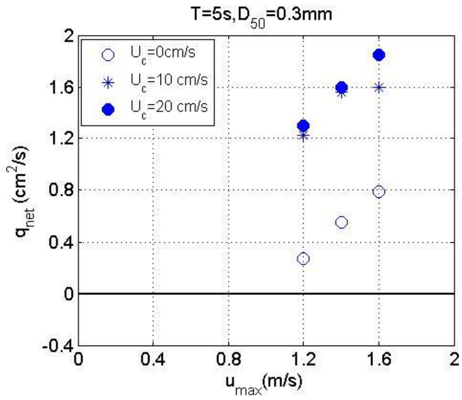

Fig. 7. Net transport rate as a function of flow velocity for coarse sand

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 transport in the onshore direction.

Streaming-induced Net Transport Rate

Dohmen-Janssen *et al.* (2002) suggested the phase-lag effect in the sheetflow transport regime enhances the offshore sand movement. As aforementioned, the onshore streaming, in general, supports the onshore sand movement. Therefore, investigation on the sediment transprot under the combined wave-current flow conditions can be regarded as an interaction between these two factors, the wave factor and the current factor. Fig. 8 illustrates the relationship between the streaming-induced net transport rate and the free-stream velocity for wave period T = 5 s under the conditions of U_c =0.1 and 0.2 m/s. In the case of U_c =0.1 m/s, 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. Very fine and fine sand with a large phase-lag effect demonstrate a small increase on the net transport rate.

On the other hand, 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 transport 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.*, u_{max} >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. Under such kinds of velocity conditions, 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 onshore streaming to 0.2 m/s, for all cases, the streaming-induced net transport rate returns increasing the net rate and leads 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, the 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.

Sediment Particle Velocities

Actually, we contributed a small onshore current and performed experiment under combined wave and current conditions in OFT. Therefore, it is the reason to investigate the mean flow velocity profiles for these conditions whether it can give an explanation about the cause of the increment of onshore net transport rate due to the addition of small onshore current. Therefore, in order to obtain

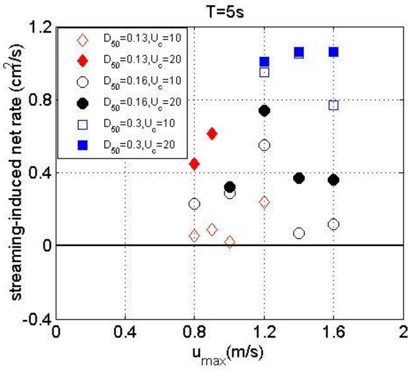

Fig. 8. Streaming-induced net transport rate as a function of flow velocity

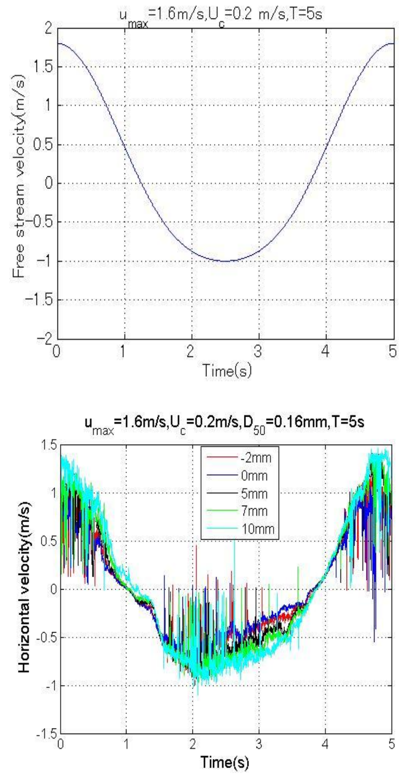

Fig. 9. Horizontal particles velocity for fine sand

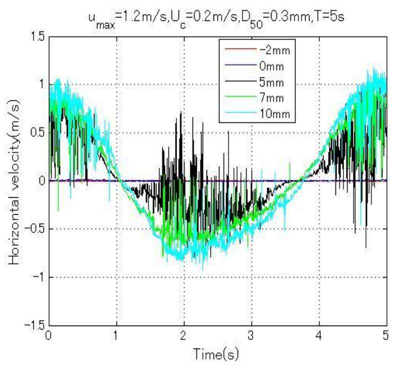

Fig.10. Horizontal particles velocity for coarse sand

new insights into the meaning of the profiles of streaming, the information of particle velocity at high concentration in the sheet flow was measured by means of PIV technique. Sediment particle velocity within the sand-laden sheetflow layer was measured by means of a PIV technique developed by Ahmed and Sato (2001). An enhanced approach of the PIV is developed on the basis of the Minimum Quadratic Difference (MQD). Figs. 9 and 10 show the results of near-bed velocity measurements of the 2nd-order stroke's wave for T = 5 s of fine sand and coarse sand together with free-stream velocity. The positive values stand for onshore velocities and the negative values offshore velocities.

The temporal variation of the velocities at five different levels from 2 mm below the initial bed level up to 10 mm above the initial bed level was estimated. Generally, the shapes of particle velocity are similar to that of the free stream flows. The results for a fine sand case are presented in Fig. 9 and for coarse sand in Fig. 10. When increasing elevation, velocity amplitudes increase gradually. At the initial bed level (z =0 mm), the velocity decreases rapidly due to the high sediment concentration.

Because of the influence of noise by using PIV, the Fast Fourier Transform (FFT) algorithm was used to obtain the vertical profiles of mean flow velocity, $U(z)$, for wave and current. In the case of U_c = 0 m/s, the results of both two different types of sand with constant flow velocity and wave period are presented in Fig. 11. From the measurements of the mean velocity profile, we can know that in the case for the coarse sand, very small positive onshore flow can occur in the pick-up layer (z< 0 mm). Sand is only mobilized around the time of maximum onshore velocity and the time-averaged velocity is positive (onshore) in this region. An offshore current is detected in the upper sheet-flow layer. The existence of the onshore mean velocity in coarse sand is the reason of wave asymmetry; the lowest levels in the pick-up layer only come into motion during the peak velocities of the onshore motion but are not mobilized during offshore flow and are therefore not affected by the negative boundary layer streaming (Ribberink *et al.* 2008).

The mean flow velocity for fine sand shows that a negative streaming is induced due to the strong phase-lag effect of fine sand in the boundary layer. The positive near-bed streaming is not observed. In addition, when the depth increases, in the region of suspension layer, the mean flow profile still continues to offshore direction as sand entrained at times of high velocity could not settle back to the bed and transported to the offshore direction. The large phase-lag can induce a negative (offshore) net transport. Thus, the phase-lag effect seems still to be presented in case of fine sand under wave conditions in OFT. Thus, the phase-lag effect seems to play an important role for the sediment sheetflow transport in OFT test. Apart from the mean flow velocities measured under

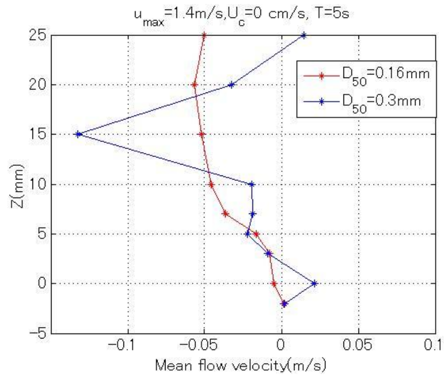

Fig. 11. Comparsion of mean flow velocity between two types of sand (U_c= 0 m/s)

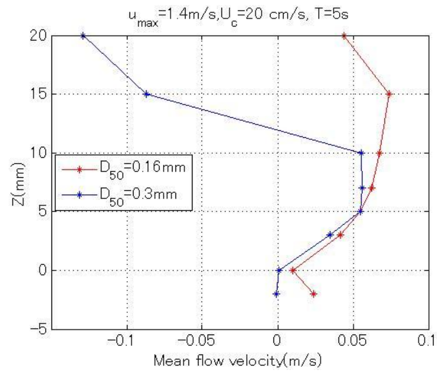

Fig. 12. Comparsion of mean flow velocity between two types of sand (U_c= 0.2 m/s)

wave, the mean flow velocity profiles are of importance under combined wave and current condition. Fig. 12 presents the results for vertical distribution of mean flow velocity with fine sand and coarse sand under the onshore streaming U_c=0.2 m/s, same flow velocities and wave period. Considering the fine sand with onshore streaming of U_c= 0.2 m/s, the mean flow profiles illustrate positive direction in the boundary layer. The magnitude of velocity is highest in the sheet flow layer for both sands.

Taking into account the coarse sand, the positive wave –induced streaming is occurred in the pick –up layer and sheet flow layer. In the sheet flow layer, more sand is carried relatively high in the flow by the higher onshore velocities than by the lower offshore velocities. However, when the depth (z) is greater than 15 mm, the mean flow profiles change from onshore to offshore direction. Therefore, an additional net onshore current could contribute to increased onshore transport. It is because when the velocity is larger, it takes long time to pick up of sediment, subsequently moved up to higher levels, the net sediment could settle and is transported to the onshore direction before the occurrence of negative velocity.

All the results of the mean profile give a positive value and lead to onshore direction in the sheet flow under combined wave and current conditions. The onshore mean flow profiles can distribute the increment of net transport rate in oscillatory flow for most of the cases. Despite an onshore streaming is observed in the boundary layer of fine sand, the offshore net transport rate was still found with the large velocity case due to strong phase-lag effect.

Conclusions

To answer the question whether the additional net onshore current contributes to a larger onshore net rate and to investigate the behavior of mean flow velocity profiles, a series of experiments was performed in the oscillatory flow tunnel and measurements of the net sand transport rate were conducted under asymmetric waves superimposed with an onshore current. The experiment results indicate that the onshore streaming, indeed, enhances the onshore net transport rate. It is also found that from the PIV analysis, under combined wave and current case, the mean flow velocity, or streaming, is directed to the onshore direction in the upper sheetflow layer while it is directed to the offshore direction in the suspension layer for coarse sand. On the other hand, for fine sand case, an onshore mean flow is observed in oscillatory flow tunnels. The mean flow velocity is always in the offshore direction in the case of wave without onshore streaming.

Therefore, we conclude that the additional onshore current in the tunnel does contribute to more onshore sediment transport. At the same time, it is also confirmed that the phase-lag effect plays an important role in the sediment transport under the sheetflow conditions, especially for the small sized sand case. 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.

References

Ahmed, A.S.M., Sato, S., (2001) Investigation of bottom boundary layer dynamics of movable bed by using enhanced PIV technique, Coastal Eng. J., 43 (4), pp.239-258.

Dohmen-Janssen, C.M. and. Hanes, D.M., (2002) Sheet flow dynamics under monochromatic nonbreaking waves. Journal of Geophysical Research.. 107(C10), 3149.

Longuet-Higgins, M.S., (1953). Mass transport in water waves. Phil. Trans. R. Soc. Lond. A, 245, 535-581.

Longuet-Higgins, M.S., (1957) The mechanics of the boundary layer near the bottom in a progressive wave, Proc. 6th Conf. on Coastal Eng., Miami, ASCE, pp.184-193.

Nielsen, P., (2006). Sheet flow sediment transport under waves with acceleration skewness and boundary layer streaming. Coastal Engineering, 53, 749-758.

Ribberink, J.S., Van der Werf J.J., and O'Donoghue, T., (2008). Sand motion induced by oscillatory flows; sheet flow and vortex ripples. Journal of Turbulence, Vol. 9, No.20, The Netherlands.

Schretlen, J.J.L.M., Ribberink, J.S., O'Donoghue, T., (2010), Boundary layer flow and sand transport under full scale surface waves, Proc. 32th ICCE, ASCE.