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On Flow Field over a Fixed Dune

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Sand Dune 주위유동장에 대하여

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Abstract

The present study deals with turbulent flow over a long train of fixed two-dimensional dunes, identical in size and shape. A detailed study was carried out by PIV over a range of flow depths in a fully developed region. The present study confirmed the global features of flow past a fixed dune noticed in previous studies, i.e. the size and shape of the reverse flow, the mean velocity and turbulence profiles across the separated and attached flows. The turbulence and shear stress profiles reveal the presence of larger values along the line extending from crest to crest. At stations ahead of the dune crest, the presence of a peak in the streamwise turbulence profiles around y/h = 2 indicates the sustenance of turbulence generated in the separation zone of the previous zone which will be carried over to the next dune.

요 약

본 연구는 크기와 형상이 동일한 2차원 모래언덕이 계속해서 이어지는 2차원 난류유동장의 해석에 관한 연구이다. 실험은 완전발달 유동장이 형성된 Flume에서 PIV를 사용하여 진행되었다. 모래언덕의 모형은 강화유리로 제작되었으므로 그 형상은 흐름에 의하여 변하지 않는 경우이다. 연구를 통하여 모래언덕을 지나는 유동의 일반적인 특성들을 재확인할 수 있었는데, 여기에는 재순환영역의 크기, 유동박리 영역과 재부착영역 등이 포함된다. 언덕의 정상 (y/h=1) 부근을 따라 유동방향으로 난류와 와도가 매우 크게 얻어졌으며, 뚜렷이 구별되지는 않지만 y/h=2 부근에는 그 전 언덕들로부터 전달되어진 난류유동특성을 확인할 수 있었다.

Keywords: Sand Dune (모래언덕), PIV (입자영상유속계), Turbulent Flow (난류유동).

1. INTRODUCTION

A prominent feature in many natural open channel flows with sediment transport is the formation of dunes. Knowledge of turbulent flow over sand dunes is required to understand the interaction between the flow, the bed form and sediment transport. It is also important to relate channel resistance to flow conditions to develop practical methods to

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predict sediment transport and channel capacity. Precise prediction of flow over dunes is of fundamental importance in many areas including geophysics, sedimentology and paleoenvironmentology. As a first step towards developing a comprehensive understanding of flow in natural channels, researchers have studied the fluid dynamics of flow over a train of fixed, well-developed dunes.

The present study deals with turbulent flow over a long train of fixed two-dimensional dunes, identical in size and shape. A detailed study was carried out by PIV over a range of flow depths in a fully developed region. Besides the mean velocity field, the variables of interest include the Reynolds stresses, triple-correlations, vorticity maps and analysis of events in the four quadrants.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The flow field was generated in a rectangular cross-section (610 mm × 610 mm), 10-m long, recirculating open channel flume at IIHR-Hydroscience and Engineering. A settling tank and a contraction precede the rectangular channel. The flume terminates in a diffusing section and a collection tank. A train of two-dimensional fixed dunes was attached to the bottom of the channel starting near the entrance to the flume and extending throughout the length of the flume. The dunes are identical in shape and size, and geometrically similar to that used in the earlier experimental study of Mierlo and de Ruiter[1988] and subsequent numerical studies of Yoon and Patel[1996]. PIV measurements were carried out in the flow between the 17th and the 18th dunes, where the flow was periodic. A simple schematic of the flow over the dune and co-ordinate system adopted is shown in Fig. 1. The depth of flow over the dune crest was $d/h=7$, where dune height h = 20mm. The Reynolds number based on the dune height ($Re = U_o h/\nu$) was held nearly constant at 1.0×10^4. Here, U_o is the reference velocity (0.5m/s) as well as the maximum velocity, which occurs near the free surface.

A 5W Ar-Ion laser was used to power the PIV system. A system of mirrors and lenses were used to generate a 3-mm thick vertical light sheet in the streamwise direction at the measuring section. The Plexiglas dunes facilitated the transmission of light and illumination of the flow field. Vinyl chloride polymer particles (mean diameter 30 mm) were introduced in the flow. An acousto-optic modulator (AOM) was used to enhance the dynamic range of velocity tracking. The camera was fitted with a zoom lens with FL range of 50 to 400 mm lens and the object distance was adjusted to obtain a field-of-view of 120 mm in x-direction and 80 mm in y-direction. The flow field over a dune was divided into five different fields of view (FOV) with a 20 mm overlap between adjacent

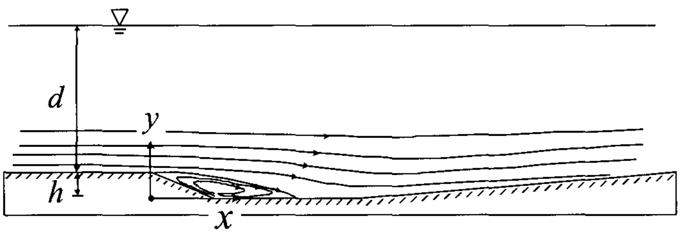

Fig. 1 Coordinates and Schematic of Flow Field.

FOVs. The time interval between two images was set to 4 ms and the exposure time to 2.2 ms. A black & white frame grabber board (Data Translation DT 3155) was used to capture the images of 640 × 480 pixel and store them with 256 gray levels on a computer. The total 1000 frames were captured for each FOV with the standard frame rate of 30. A commercial software (Thinkers eyes 2-D) was used to perform the image analysis using a gray-level cross-correlation technique.

3. RESULTS

Fig. 2 shows the mean streamlines obtained using PIV for d/h = 7. The mean velocity vectors over the wavelength of the dune are also superimposed in Fig. 2, while Fig. 3 shows the mean vorticity contour maps. Together, they serve to illustrate the characteristic features of the flow. The flow field involves a region of high vorticity ahead of the dune crest due to the presence of a near-wall boundary layer, flow separation at the dune crest with regions of high vorticity along the separating shear layer, a characteristic recirculating region near the lee side of the dune, a decelerating wake-like flow riding over the separation cell, and the development of a new boundary layer following reattachment of the flow on the stoss side of the dune. One cannot define a well-defined streamline originating from the crest and ending on the bed, making it difficult to precisely define a mean reattachment point. Visual placement of this point is deceptive because the near-wall streamlines in the separation zone suggest the possibility of flow converging into the plane of symmetry. Fig. 4 and 5 show the streamwise turbulence intensity and shear stress contour maps, respectively. The contour map of the

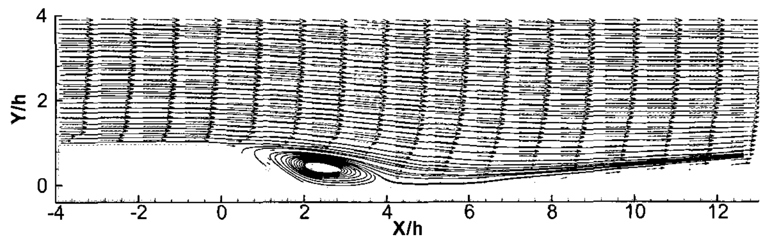

Fig. 2 Mean Velocity Vectors and Streamlines.

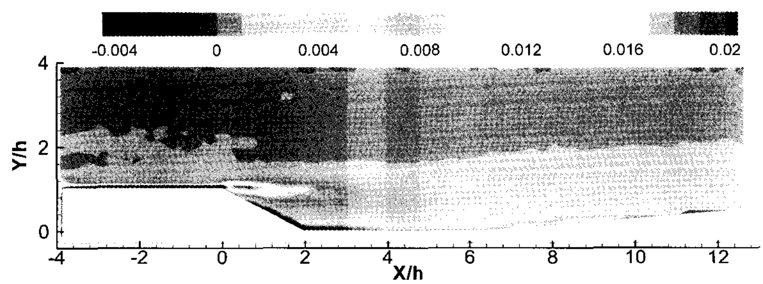

Fig. 3 Vorticity Field.

streamwise turbulence intensity indicates the presence of maximum values along a line extending from one crest to the next (denoted as crestline) in the vicinity of the separating shear layer. Along the crestline, there is a gradual decay in the turbulence intensity, but the rate of decrease is slow. The mean shear stress contour also indicates large values along the crestline. The general information provided by these figure confirms previous studies of flow over dunes (e.g., Bennet and Best[1995]). However, this set of data, is perhaps the most complete set detailing the whole field mean flow information.

Earlier experimental studies have noticed the occurrence of dune-related bursting or ejections and field investigations have noted the formation of large eddies downstream of the dune crests with high concentrations of suspended sediment. To further quantify the differences in turbulence structure due to the varying depth of flow over the dune, a quadrant analysis using the method of Lu and Willmarth[1973] was carried out. To detect data in the four quadrants that lie outside the hole, a detector indicator function was defined such that

$$\lambda_Q(t) = \begin{cases} 1 & \text{when } |uv|_Q \geq H\,(u)\,(v) \\ 0 & \text{otherwise} \end{cases}$$

Here, Q denotes the quadrant of interest. With this scheme, only the large contributions to <uv> from each quadrant can be extracted leaving the smaller fluctuations in the hole region (corresponding to more quiescent periods). The contribution to <uv> from a particular quadrant may then be written as:

$$\langle uv \rangle_Q = \lim_{T \to \infty} \frac{1}{T} \int_0^T (uv)\, \lambda_Q(t)\, dt$$

In this paper, results are presented for H = 2.0, which corresponds to events which are associated with (u)(v) > 5.5 <uv>.

It has been noted in earlier studies that the contributions of Q2 events are very important

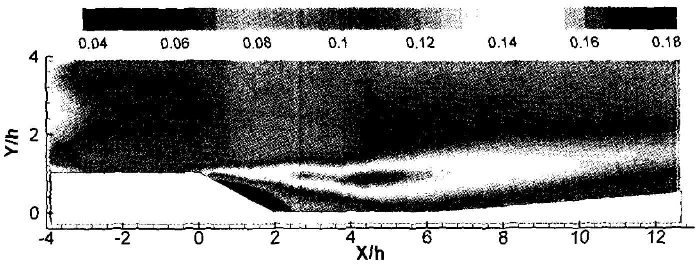

Fig. 4 Streamwise Turbulent Intensity.

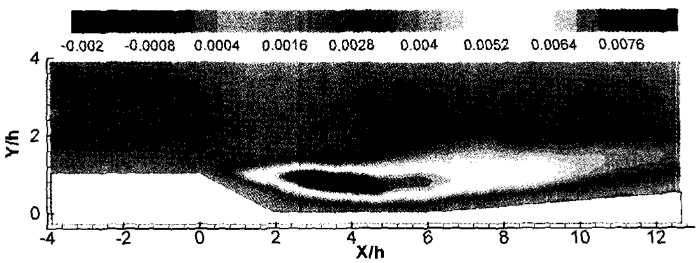

Fig. 5 Shear Stresses.

and have been associated with much of the entrainment and transport of sediment. The contributions by quadrant 2 (Q2) events are dominant at all X/h locations in Fig. 6. With increasing distance from the crest, the Q2 profiles indicate the presence of large gradients. Similar to Q2 events, Q4 events show large changes in the vicinity of the shear layer. For y/h < 2.5, the Q4 profiles show a trend that is opposite to that noted in the Q2 profiles. Ahead of reattachment (X/h = 2 and 4), above the crestline, the magnitude of the Q4 events tend to be close to the Q2 events.

4. CONCLUSIONS

The present PIV measurements confirm the global features of flow past a fixed dune noticed in previous studies. The size and shape of the reverse flow, the mean velocity and turbulence profiles across the separated and attached flows, are well described by the PIV data. The flow is periodic in space insofar as the flow pattern is the same over successive dunes; there is significant variation in flow properties along the wavelength of the dune. However, the mean velocity profiles show the existence of an outer region that is similar at all depths but different from that of a traditional open channel flow. The turbulence and shear stress profiles and contour maps reveal the presence of larger values along the line extending from crest to crest. At stations ahead of the dune crest, the presence of a peak in the streamwise turbulence profiles around y/h = 2 indicates the sustenance of turbulence generated in the separation zone of the previous zone which will be carried over to the next dune.

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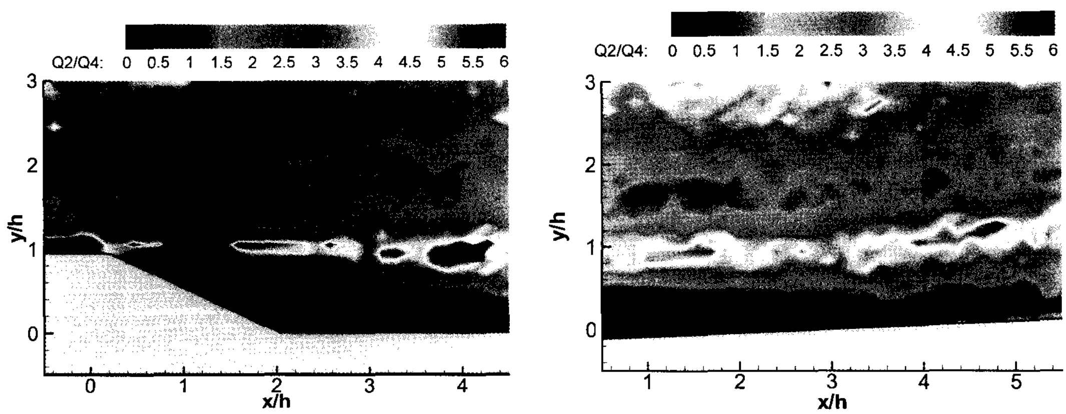

Fig. 6 Examples of Quadrant Analysis.

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