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Flow measurements in a simulated estuary bed

by

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ABSTRACT

The present work reports an experimental investigation carried out on a mini flume of 130 mm outer diameter. In this apparatus, in which a tangential turoidal flow is induced, one aims to simulate in laboratory, flow conditions similar to those observed in a natural estuary bed. The data were taken using a commercial 2D LDA system, enabling the simultaneous measurement of two velocity components. In the present experiments, it was investigated an aqueous solution of glycerine whose characteristics resemble those of the sediment laden fluid. It was also investigated the effect of a rough bed, moulded on a natural sediment. Various Reynolds numbers were investigated. The results show that local turbulence is closely linked to the onset of erosion. The presence of a rough wall increases the local turbulence levels and the occurrence of recirculation pockets in its vicinity.

1. INTRODUCTION

Coastal regions are of great importance to both human communities and natural ecosystems. Therefore, understanding the dynamics of these regions is of strategic relevance, particularly if these processes are linked with other large scale scenarios: climate change, pollution. The erosion of coastal sediment and the transport of suspended material is a critical factor in the prediction of change to coastal environmental systems. The dynamics is a balance between the cohesiveness of the sediment and the flow driven shear at the interface. The stability of the sediments is primarily controlled by the biological activity of diatoms through the exudation of extracellular polymeric substances. The onset of erosion occurs when the shear stress exceeds a critical value. Although turbulent flows lead to sediment erosion, it has been observed that in laminar flows, erosion may also occur.

Over the recent years, many studies have been dedicated to the study of the erosion process. It is clear from recent studies that sediment erosion is mediated by biological factors (Paterson, 1994). This process may dominate grain-grain interactions and subsequently control the sediment stability. Measurements of such physical characteristics have been carried out both in field and in laboratory using circular flumes (Graham et al, 1992). The occurrence of secondary flows due to flow curvature must be accounted for, though it has been shown that a circular flume has various advantages over linear flumes (James and Jones, 1992, 1996). The required accurate characterisation of the flow has shown that measurements of shear stress using stress probes mounted on a controlled shear rehometer are well related with the velocity field, once this is properly defined.

However, there is an important lack of knowledge in understanding the fundamental physical phenomena concerning the erosion of sediments. Of particular relevance are the conditions leading to the onset of erosion and the relationship between these phenomena and the mud rheology. Based upon the evidence from other fields, a few parameters may be identified by their relevance to the phenomena. It is clear that the local flow structure near the interface plays an important role in the breakdown of the sediment. There is strong evidence (Azzopardi and Teixeira, 1994, amongst others) that the presence of a dispersed phase/particles (through size, concentration) is linked to the turbulent structure of the flow. In addition, the surface topology will affect the local flow patterns and, therefore, the erosion process. Also, the wavy surfaces (Thais and Magnaudet, 1996) may induce flow patterns that may interfere with the shear layer near the sediment. These phenomena must also be addressed in the context of a deformable bed (it does not behave as a perfect solid wall) and a fluid whose rheological properties may be modified as a result of the entrained suspended matter (Di Felice, 1999).

From this experience, it may be concluded that mini flumes provide a well constrained hydrodynamic environment to investigate the influence of various physical phenomena. In order to study these relationships through a detailed characterisation of the flow field, an experimental programme must be implemented on a system that duplicates the phenomena described above, what may be described as a *simulated bed*. However, their various contributions may not be possible to be verified simultaneously. Therefore, a possible approach is to isolate the various physical contributions and evaluate each one of them per se. The discussion upon the the most effective approach is the object of discussion in subsequent sections.

2. EXPERIMENTAL DETAILS

The experiments were carried out using a toroidal flume, whose design has been extensively used in critical shear stress measurements in sediment beds (Graham et al, 1992). With this design, the flow characteristics observed near the sediment can reproduce those observed in natural beds. Basically, it consists of two concentric tubes, 70 mm high. The internal diameter of the outer tube is 129 mm and the outer diameter of the inner wall is 60 mm. The walls are 3 and 6 mm thick for the outer and inner, respectively. Although the inner tube is made of Perspex, the outer is built in quartz for better optical access. The flume is enclosed in a square tank to minimise the optical distortions due to mismatch in the refractive index. A circular lid linked to the shaft of a Physica MC100 rehometer on top of the toroidal channel drives the fluid on a tangential flow at controllable speeds. A schematic arrangement is shown in Figure 1.

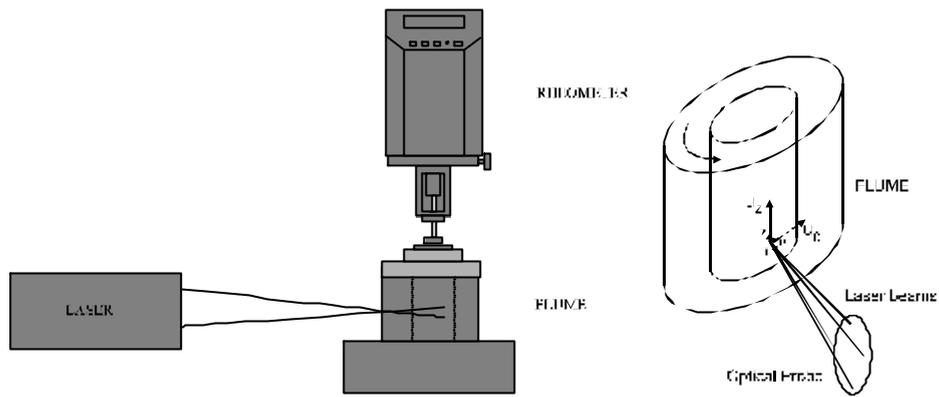


Figure 1 – Schematic view of the test section

The velocity field was measured using a two colour/four beam – two component LDA system. In this, a water cooled, 5 W, Argon-Ion laser beam is splitted into two colours (514.5 and 488 nm) and the resulting beams are steered into the transmitting optics through a fibber optic cable, 5 m long. The transmitting lenses are standard Dantec 310 mm in focal length resulting in a half angle between the beams of 7.08° . Flow direction sensitivity is provided through 40 MHz Bragg cells on both components. For convenience, the scattered light is collected in the backscatter mode through the same 310 mm lens and steered through the fibber optical cable into two photomultipliers. The transmitting/receiving optics are mounted in a 3D programmable traversing table and the Doppler signals were processed through a couple of spectrum analysers (Dantec BSA's 55x models). Polyamide particles (mean diameter of 20 μm) whose density is close to that of water (1030 kg/m^3) were used as seeding particles. Figure 2 shows a schematic view of the optical experimental arrangement. The resulting probe volume is 0.06 mm in diameter and 0.8 mm long. The beams have an expansion factor of 1.95.

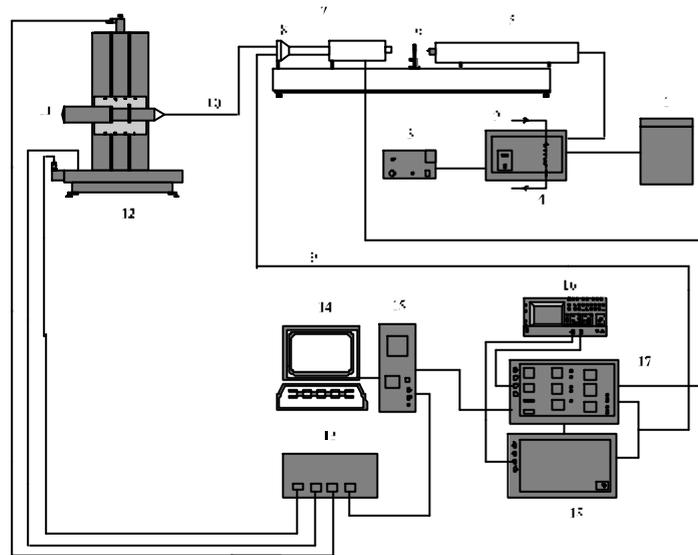


Figure 2 – Schematic layout of the LDA instrumentation

- | | | |
|-----------------|----------------------------------|-----------------------------|
| 1- Transformer | 7- Beam separator and Bragg cell | 13- Traverse controller |
| 2- Power supply | 8- Fibber manipulators | 14- Monitor |
| 3- Controller | 9- Scattered signal | 15- Computer |
| 4- Water flow | 10- Fibber optic | 16- Oscilloscope |
| 5- Laser head | 11- Transmitting optics | 17- Burst Spectrum Analyser |
| 6- Shutter | 12- 3D Traverse table | 18- Burst Spectrum Analyser |

Figure 3 shows an overall view of the entire experimental set-up.

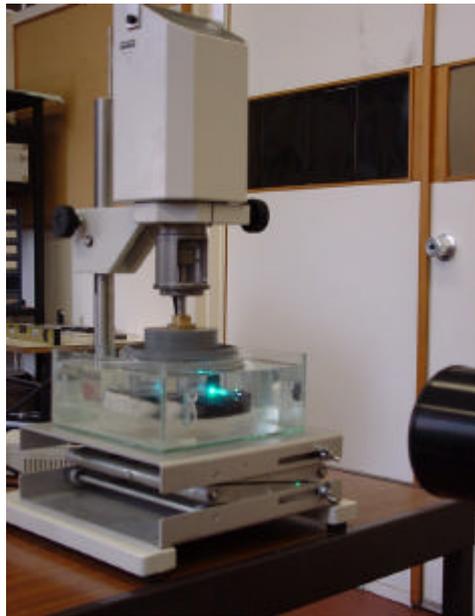


Figure 3 – Test rig

3. TEST CONDITIONS

In order to reproduce in laboratory the conditions observed in the vicinity of an estuary sediment, a comprehensive physical characterisation of the interface was undertaken. The ultimate objective is the use of a suitable fluid both from the physical properties point of view and that of optical compatibility.

Firstly, mud samples were collected at an estuary at low tide into a mini flume of the same design as reported in the previous section. The gap between the sediment and the circular lid was filled with river water and this set up was driven at various rotation speeds. From these tests, it was possible to infer the speed at which erosion would occur, in addition to the stress levels in the bed. Furthermore, high speed video movies (500 *fps*) were taken during these experiments. Such tests provided valuable insight into the physical mechanisms which appear to be dominant at the onset of erosion and are in line with the hypothesis outlined above (Section 1).

During the erosion of the bed, sediments are entrained into the moving fluid, increasing its concentration with time. Therefore, it was evaluated the effect of the suspended matter (at various concentrations) upon the fluid rheological properties. In addition, the tests were carried out with various sediments, sampled at different sites. From this set of tests, it was concluded that the sediment laden fluid has a viscosity varying from that of pure water to that of a Bingham type fluid. Figure 4 shows the results concerning the apparent viscosity at increasing shear rates.

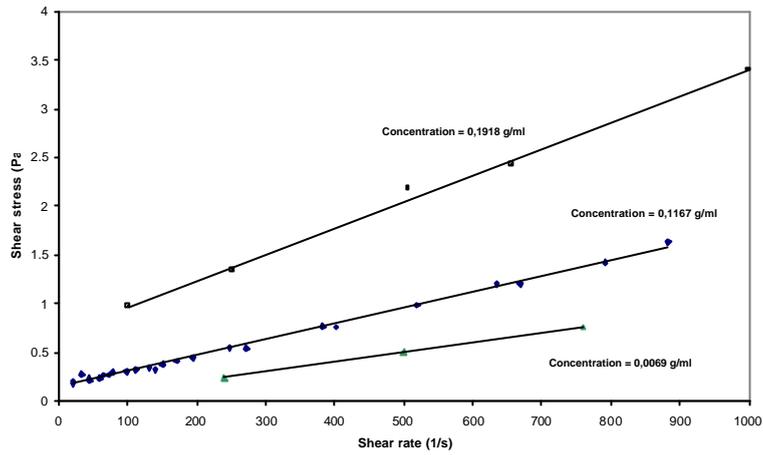


Figure 4 – Apparent viscosity versus shear rates for sediment laden fluids

The differences are primarily related with the type of sediment, where the presence of finer suspensions shows a stronger deviation to that of the water. The particle size was measured using a laser diffraction based instrument and the results are shown in Figure 5. Furthermore, the data shows that the particle concentration (that is, the level of sediment erosion) has influence. Based upon these results it was decided that a low viscosity fluid should be employed. A 0.3662 g/ml aqueous solution of glycerine would yield a viscosity of 0.003 N/sm. This analysis casts some concern over the application of high viscosity fluids which has been used in the past (James and Jones, 1996). Such an approach would lead to low Reynolds numbers flows where turbulence might be absent.

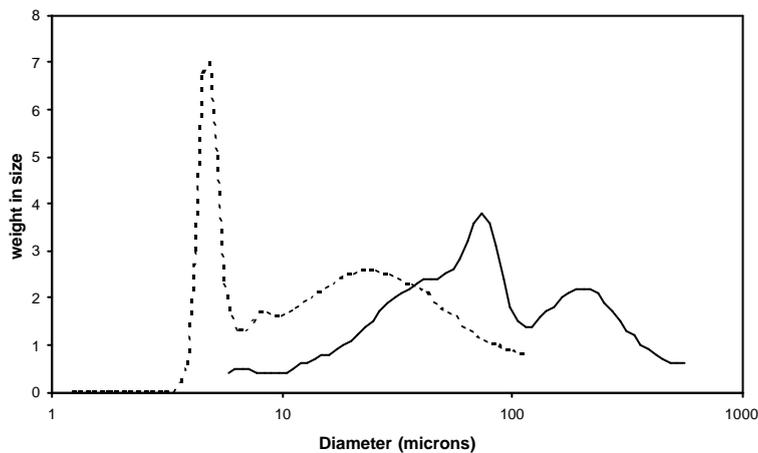


Figure 5 – Particle size distribution in the sediment

Tests were carried out at Reynolds numbers of approximately 240,000 and 120,000 which reproduce conditions close to those observed when the bed is completely eroded and when the process is active, respectively.

Furthermore, the velocity measurements were undertaken with a model of the sediment, used as the lower wall of the flume. This wall was moulded in gypsum onto a sample of sediment. In this way, the roughness and shape of the sediment bed are accurately reproduced.

For each position inside the test section, two components of the velocity were measured simultaneously. Velocity statistics were based upon samples of 5,000 data points. Information on the mean velocity, turbulence and Reynolds stresses was obtained.

4. RESULTS AND DISCUSSION

Figure 6 shows the tangential velocity field at $Re=120,000$ on a flow over a smooth bed. The velocity profile along a radius is skewed to the outer wall, as a result of the centrifugal forces. Because the flow is driven from the top layer, this pattern is more evident in those regions. Such flow pattern induces stronger velocity gradients near the outer wall, as observed in Figure 7. The influence of the flow Reynolds number is shown in Figure 8 for the tangential velocity field. It is observed that the skewness of the velocity field towards the outer wall is stronger than at a lower Re .

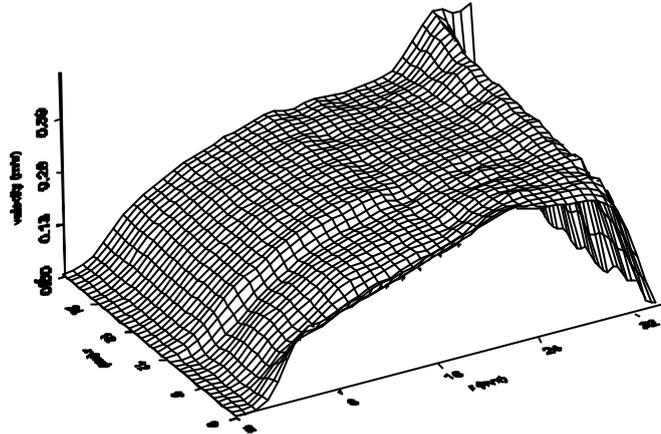


Figure 6 – Tangential velocity; $Re=120,000$

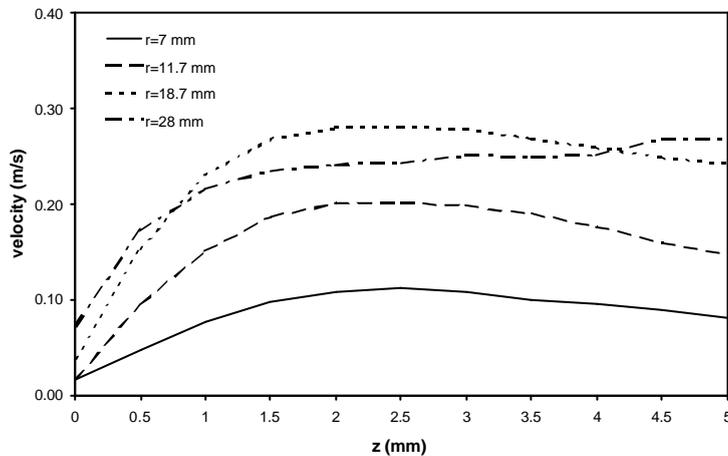


Figure 7 – Tangential velocity profile; $Re=120,000$

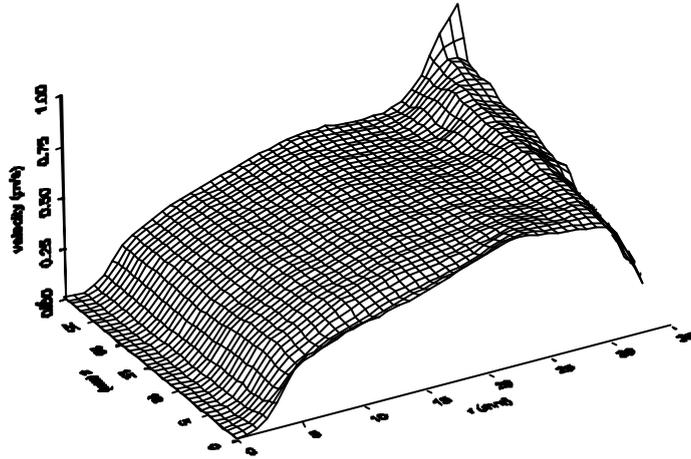


Figure 8 – Tangential velocity; $Re=240,000$

Figures 9 and 10 show the velocity field for the crosswise component of the velocity. It is observed that at both Reynolds numbers, a recirculation pattern is present near the outer wall. As Re increases, it is shown that the recirculation zone: a) is pushed outwards; b) is stronger (that is, the component of the secondary flow is more important by a factor of approximately 2) and c) occurs over a smaller area. These observations are consistent with other data. Measurements taken in a flume of similar design but with very high viscosity fluids, indicate that the recirculation zone is spread over the entire cross section of the torus. In addition, other recent data taken by the authors at higher Reynolds numbers show that the trend reported above is even more evident.

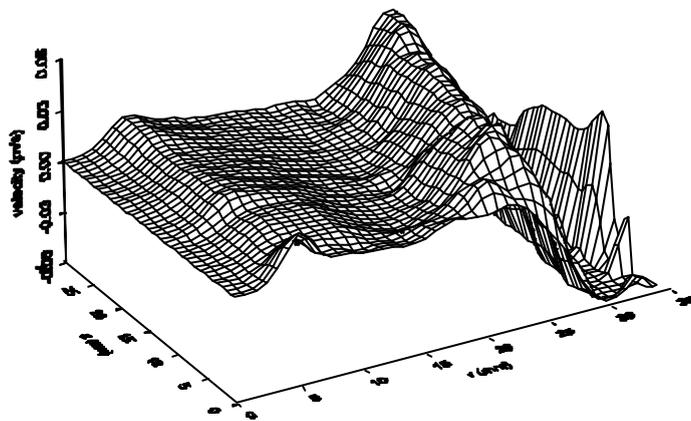


Figure 9 – Crosswise velocity field; $Re=120,000$

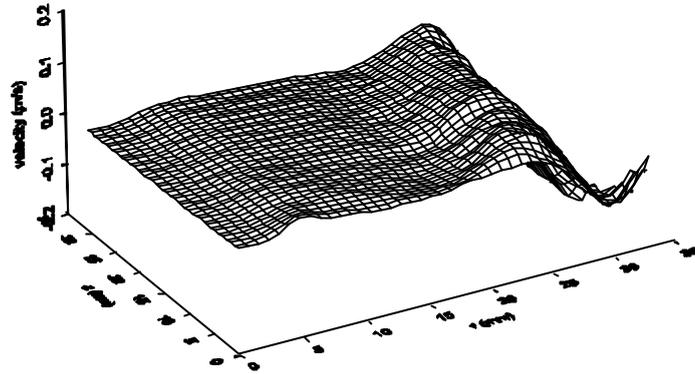


Figure 10 – Crosswise velocity field; $Re=240,000$

Visual evidence (from the high speed video movies taken over various samples) indicates that the onset of erosion occurs systematically at the outer edge of the cross section. This observation is consistent with the fact that the overall shear will be greater in that region as a result of the secondary flow pattern previously discussed. But, more importantly, as shown in Figures 11 and 12, the turbulence levels are always higher in this part of the flow. This clearly shows that erosion is a local turbulence driven mechanism as opposed to a process controlled by the mean bulk characteristics of the flow. At $Re=240,000$ the *rms* of the streamwise velocity component is also much greater than at $Re=120,000$ and is present over a larger area of the bed, into regions closer to the inner wall. This is consistent with the finding that turbulent energy production is located primarily in those regions (Figure 13). The observations for the other *rms* values of the crosswise component show a similar behaviour. In addition, the data shows that turbulence is isotropic.

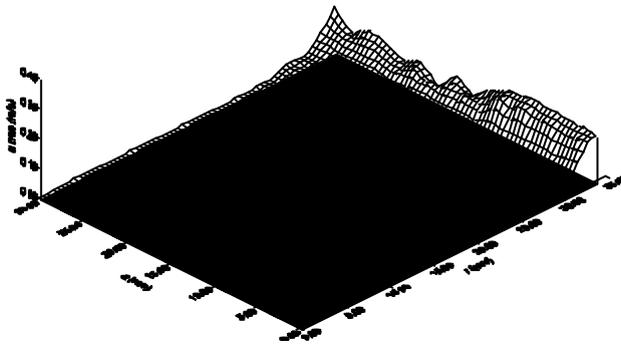


Figure 11 – Tangential velocity turbulence; $Re=120,000$

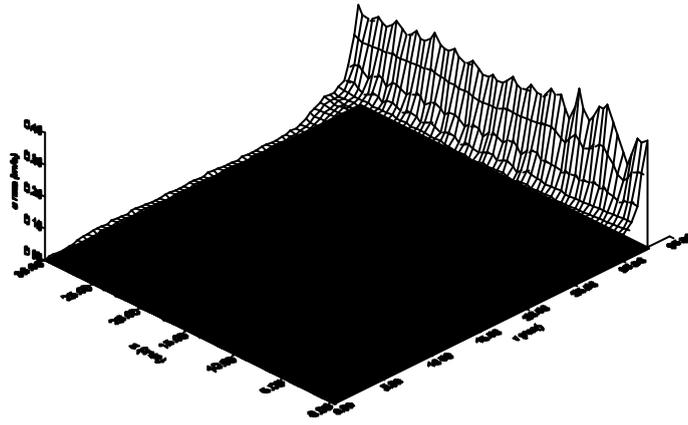


Figure 12 – Tangential velocity turbulence; $Re=240,000$

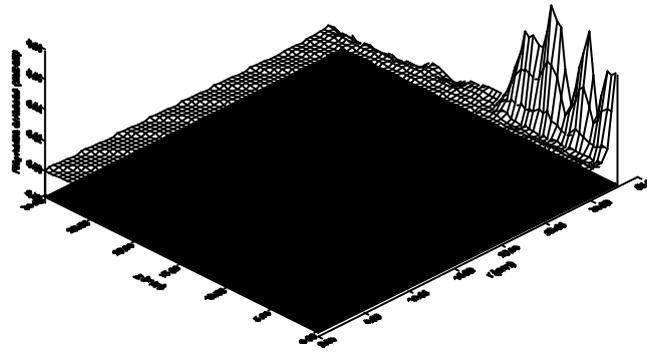


Figure 13 – Reynolds stresses; $Re=240,000$

With the experiments with a model bed, it was attempted to investigate the influence of the surface shape and roughness upon the the flow patterns in the vicinity of the bottom wall. Figure 14 depicts the mean tangential velocity ($Re=120,000$). In this, the shape of bed surface is clearly visible, by the location of the zero velocity points. The influence of the bed surface is observed on the strong velocity gradients in its vicinity. As a consequence, recirculation is due to both the outward driven flow and that locally induced by the bed topology, which occurs along the flume cross section (ζ direction), as observed in Figure 15. Comparing with the flat bed situation, turbulence is enhanced by a factor of approximately 50%. Furthermore, high turbulence levels are observed along the bed surface (Figure 16) as opposed to those observed with the flat bed, in which high turbulence levels are primarily located near the outer wall (Figure 11). Regarding the other velocity components, the data concerning the *rms* velocity show a similar pattern. These observations are consistent with the hypothesis outlined above that local turbulence is the prime mechanism leading to flow induced sediment erosion.

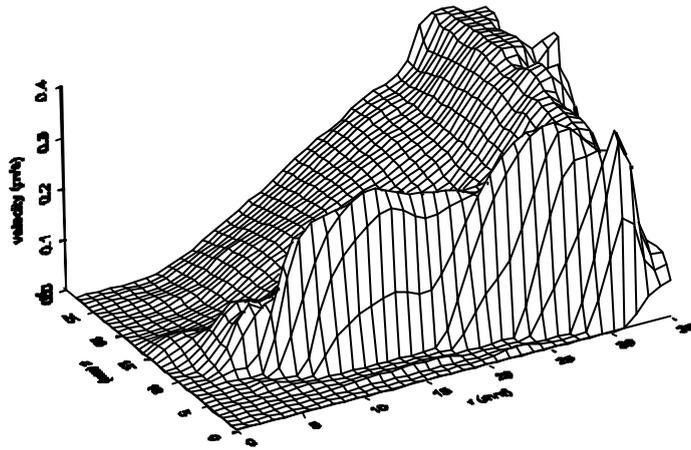


Figure 14 – Tangential velocity near a rough wall; $Re=120,000$

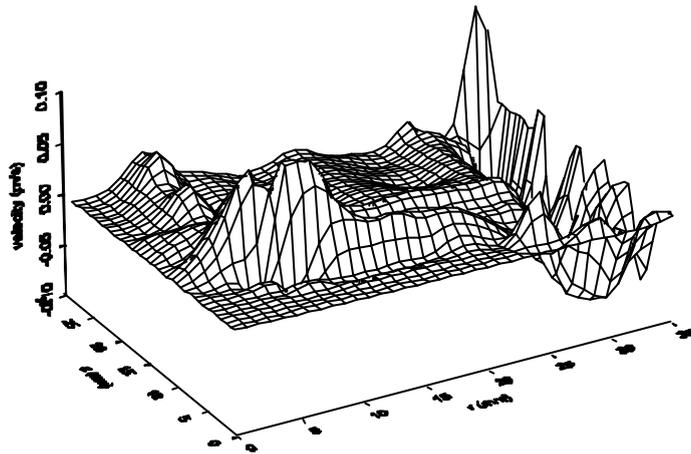


Figure 15 – Crosswise velocity field near a rough wall; $Re=120,000$

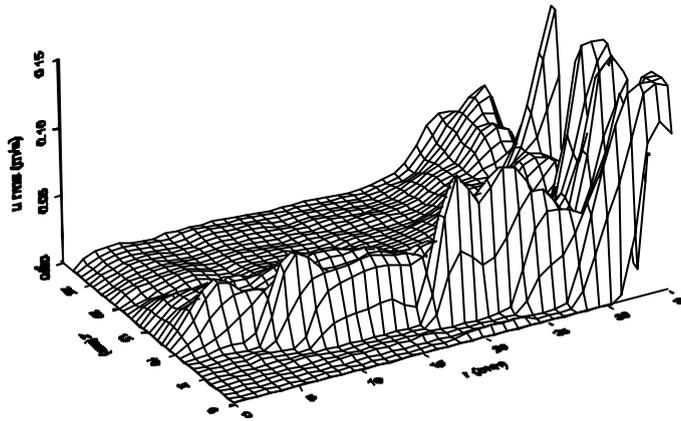


Figure 16 – The effect of a rough wall upon the streamwise turbulence; $Re=120,000$

5. CONCLUSIONS

The present work reports an experimental investigation, using a two component laser anemometry system, upon the flow characteristics observable in a sediment bed. From the results obtained, some conclusions can be drawn.

The experimental evidence strongly confirms the influence of the local flow structures (turbulence, recirculation patterns) in the region near the sediment bed upon the initialization and enhancement of the erosion. This is in line with visual evidence obtained using a high speed video camera. Detailed attention has been given to the sediment shape and roughness. It was observed that the turbulence levels are significantly higher than those measured in a flat bed. In addition, high turbulence is observed throughout the sediment, which is induced by the surface shape. The flow on a toroidal flume leads to the occurrence of recirculation zones. These are shifted to the outer wall as the Reynolds number increases. The presence of a rough wall increases the number of local pockets of recirculation.

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REFERENCES

- Azzopardi, B.J. and Teixeira, J.C.F. (1994). "Detailed Measurements of Vertical Annular Two Phase Flow. Part II: Gas Core Turbulence", ASME J of Fluids Engineering, vol 116, no. 4.
- Di Felice, R. (1999). "The Sedimentation Velocity of Dilute Suspensions of Nearly Monosized Spheres", International Journal of Multiphase Flow, vol 25, pp. 559-574.
- Graham, D.I., James, P.W., Jones, T.E.R., Davies, J.M., and Delo, E.A. (1992). "Measurement and Prediction of Surface Shear Stress in Annular Flume", Journal of Hydraulic Engineering, vol. 118, no. 9, pp. 1270-1286.
- James, P.W. and Jones, T.E.R. (1992). "The Measurement and Prediction of Surface Shear Stress Induced by Newtonian and Non-Newtonian Fluids", Proc. XIth Int. Congr. on Rheology, Brussels, Belgium, 17-21 August.

James, P.W. and Jones, T.E.R. (1996). "Numerical and Experimental Studies of Annular Flume Flow", *Appl. Math. Modelling*, vol. 20, pp. 225-231.

Paterson, D. (1994). "Biological Mediation of Sediment Erodibility: Ecology and Physical Dynamics" *Intercoh'94*; CRC Press.

Thais, L. and Magnaudet, J. (1996). "Flow Structure Induced by Waves" *J Fluid Mechanics*, vol 328, pp. 314.344.