Modelling Flow over Rough Surfaces in Hydropower Waterways

Robin Andersson

Fluid Mechanics
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Robin Andersson

Division of Fluid and Experimental Mechanics
Department of Engineering Sciences and Mathematics
Luleå University of Technology
971 87 Luleå, Sweden
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Cover photo is taken by Ulrica Magnusson and depict the Aklats power station.

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or by contacting Robin Andersson,

robin.andersson@ltu.se

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ISSN 1402-1544

Luleå 2018

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This work has been carried out at Luleå University of Technology and Vattenfall Research and Development in Ålkarleby between 2014-2018. The research presented was carried out as a part of "Swedish Hydropower Centre - SVC". SVC has been established by the Swedish Energy Agency, Elforsk and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University. www.svc.nu.

Participating companies and industry associations are: Alstom Hydro Sweden, Andritz Hydro, E.ON Vattenkraft Sverige, Falu Energi & Vatten, Fortum Generation, Holmen Energi, Jämtkraft, Jönköping Energi, Karlstads Energi, Mälarenergi, Norconsult, Skellefteå Kraft, Sollefteåforsens, Statkraft Sverige, Sweco Energuide, Sweco Infrastructure, SveMin, Umeå Energi, Vattenfall Research and Development, Vattenfall Vattenkraft, Voith Hydro, WSP Sverige and ÅF Industry.

First i would like to direct gratitude towards my supervisors for their endless help during this work. Gunnar, thank you for all the help in writing the articles, the simulations and for being a good supervisor. Patrik, sometimes it seems there is no end to your knowledge and i hope to one day reach that level of insight. Sofia and Anton for the help during the experimental campaigns. Many thanks to all of the co-workers for making the department a very nice place to work and for all of our amazing ski-trips. To the crew for sticking with me during these many years i’ve spent in Luleå. Charlie and Erika for the many wonderful nights of Tacos and Skip-bo. My mother and father for always believing in me and showing me how to appreciate life. My little sister Jenny for teaching me to protect what’s important in life. Ulrica and Alice. I read once that the ancient egyptians had fifty words for sand and the eskimos had a hundred words for snow. I wish i had a thousand words for love, but all that comes to mind is falling asleep next to you and there are no words for that.

"May you choices reflect your hopes, not your fears"
Robin Andersson
Luleå, November 2018
Through the never.
Part I

Summary
Introduction

During the past half century the hydropower industry has experienced significant growth in Sweden. Today hydropower accounts for roughly 40% of Sweden’s annual supply of electricity (Energiföretagen, 2018), about 2.5% worldwide (International Energy Agency, 2018) and it is an industry under constant growth. Due to the expanse, vast systems of water conveying tunnels have been excavated. Many of these tunnels are old and their survival is often vital to the system in which they are situated. Rock falls is the event of quantities of rock falling from the tunnel walls or roof. A certain amount of rock falls within unlined hydropower tunnels are acceptable and largely unavoidable (Bratveit et al, 2016). In most cases it is a cost-benefit assessment where eventually the incremented friction losses become unacceptable and the tunnel has to be refurbished. Lining the water tunnels using methods i.e. concretion will strengthen the tunnel walls and make them smoother, but the method is expensive and the eventual loss in cross sectional area may defeat the intended friction loss. It is not uncommon for tunnels to collapse, even after 30-40 years of usage (Reinius, 1986). One reason for tunnel-instabilities is hydropoeaking. The increasing demand for renewable energy lead to uncertain production patterns for hydropower which will increase the load on the tunnels. (Bratveit et al, 2016). Another theory is the localised flow effects arising due to the flow-roughness interactions. Studies such as Andersson et al (2016, 2018) have shown increased localised fluctuations of pressure and velocity connected to roughness elements. Similarly, a study by Patel et al (2017) showed that cyclic injection of fluid into rock walls led to breakage at lower magnitudes of pressure than static injection. In that case, the current industrial standards for evaluating surface roughness has to be adjusted accordingly. So what is the difference between an unlined hydropower tunnel and a regular rough pipe? Numerically they are more often than not treated the same in the industry. The roughness in the traditional sense, i.e. the industrial view, is regularly assumed to be mainly friction inducing and its effects are accounted for as a spatially averaged component (Jimenez, 2004). While the net-effects on the flow due to the roughness might be correctly estimated this way, the instantaneous effects are attenuated through spatial filtering.

When modelling river systems or free surface flows in channels, knowledge of the inlet and roughness conditions is important. With no surface roughness present the entrance length can accurately be estimated using a variety of methods. The introduction of surface roughness will lead to an increase in dissipation (Mansour et al, 1988) leading to a more efficient homogenisation of the flow.
CHAPTER 1. INTRODUCTION

Naturally, any perturbations induced at the inlet will dissipate more rapidly in the vicinity of the rough surface and at lower depths. Hence, when modelling certain flows, such as relatively shallow rivers or tunnels of sufficient roughness, proper modelling of the surface roughness becomes increasingly important.

Hydropower tunnels are a very hostile environment to measure within. As a result, accurate velocity or pressure measurements in situ are rarely possible and experimental results on natural surfaces of large-scale roughness are scarce. This problem was highlighted by Grass (1971) but to a large degree still remains today. Computational Fluid Mechanics (CFD) offer possibilities to estimate flow effects within the tunnels. However, since the dynamics within the tunnel are largely unknown the validation is a significant problem. Additionally, the resulting domain is usually large and the computer cost will be significant even for a relatively coarse mesh. Two different modelling approaches have been applied in this study. A Reynolds Averaged Navier Stokes (RANS) approach with $k$-$\varepsilon$ model for turbulence closure and an Large Eddy Simulation (LES) approach. While the RANS approach is numerically cheap and very popular in the industry, there are a number of drawbacks associated to it. One drawback is decreased accuracy in the presence of strong adverse pressure gradients. The approach has also been shown to under-predict shear layers generated by separation as shown in ERCOFTAC (2000) and Andersson (2013). The approach is however known to capture the main flow dynamics in connection to roughness characteristic for hydropower tunnels. The basis of LES is to decompose the velocity into a resolved and residual component. In short, the large scale motions are directly represented by the equations and the smaller dissipative scales of motion are modelled. This approach is more computationally demanding than the RANS approach but less than Direct Numerical Simulation (DNS). The mesh has to be adapted according to the turbulent spectra. Knowledge of the flow situation is therefore required before performing the simulations, hence, LES has to be performed in connection with other turbulence models.

A range of experimental techniques has been applied in this study including Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV), Acoustic Doppler Velocimetry (ADV) and pressure measurements. PIV involves illuminating particles suspended in the fluid using a laser. The particles can now be photographed using a high speed camera. Computer software will then statistically track group of particles to produce a visualization of the flow field. While PIV is Eulerian, PTV is a Lagrangian method where floating particles of significantly larger size where used. The main difference is that PTV tracks individual particles, generally less particles are needed and no laser is used for illumination. ADV utilize a probe inserted into the desired medium which measure the doppler shift in a small area, averaged as a point. The method is relatively intrusive, but can provide high frequency point measurements of all three velocity components within the flow.

The goals of this work has been to: (i) To visualize the effects of surface roughness in order to evaluate the current industrial standards for treating surface roughness. (ii) To evaluate how to properly model and measure the flow in hydropower tunnels or channels. (iii) Investigate the importance of inlet conditions in relation to surface roughness. (iv) To validate the experiments with a case study.
This chapter details the three experimental and numerical setups used in this work. The first setup was the investigation of a rough surface opposed to a smooth wall. The second setup was the investigation of inlet perturbations in connection to surface roughness. The third setup was a numerical case study employing a tunnel located in Gävunda.

2.1 PIV and pressure measurements

The experimental setup is a closed loop system whose main components are a pump, a rectangular channel, a downstream tank collecting the water, an upstream tank controlling the head of the system, a PIV system, pressure sensors and a magnetic flow meter. An overall schematic of the experimental setup can be seen in Fig. 2.1.

![Figure 2.1: A schematic of the experimental setup used in the campaign. The figure is not to scale and the channel has been mirrored to provide a more comprehensible view regarding the setup.](image)

The rough surface model used in both the experiments and the simulations is a side wall of an existing rock tunnel whose topography was captured by high-resolution laser scanning (≈200 points/m²) and scaled down to 1:10. The rough surface with the position of the PIV-plane and pressure sensor detailed can be seen in Fig. 2.2.
CHAPTER 2. GENERAL SETUP

Figure 2.2: The rough surface in the measuring section, the cyan line marks the position of the plane captured by the PIV and the cyan circle marks the position of pressure sensor 6, see Fig 3.6. The colour of the surface represents the relative gradient ($dh/dx$) of the surface topography.

In the middle of the plane, a roughness element in the shape of a ridge can be observed. This roughness element is of special interest due to its shape and size and will henceforth be referred to as "the ridge". A honeycomb is placed at the entrance of the channel to provide homogeneous flow at the inlet.

Figure 2.3: The channel with the downstream tank visible.

The flow is pressure driven and the head is regulated by the water level in the cabin visible in Fig. 2.4. The water level was controlled via a valve positioned under the cabin, before the bend leading to the channel inlet. The pump was connected to a PID-regulator and a magnetic flow-meter, allowing effective control of the flow rate through the channel. The magnetic flow meter used was an IFS4000 from Krohne connected to an IFC 110 signal converter. To calibrate the pressure sensors, the outlet of the channel was completely closed while altering the water level within the cabin.
2.2 PTV and ADV measurements

In this experiment, the setup consists of a flume, pump, two magnetic flow meters and a measuring system. Both walls and the floor of the surface is replaced with a surface of considerable roughness, similar to Sec. 2.1. The roughness is not natural but is generated using the diamond square algorithm, see Sec. 5.2.2. The width of the channel is on average 1.2 meters and the length is 17.5 m. After 17.5 m all three surfaces are flat at z=0 (average roughness height of the channel), this is the outlet section. The different water depths are controlled through an inclined plate at the outlet downstream of the flat surface. For even illumination of the flow, an LED ramp has been mounted above both the left and right edge respectively, visible in Fig. 2.5.

A baffle with three plates was placed at the inlet of the flume. Two perforated sheets were placed upstream of a third sheet of honeycomb type, see Fig. 2.6.
The perforated sheets have a hollow radius of 2 and 1 cm respectively, while the honeycomb has a radius of 3 cm and a thickness of 29 cm. During some of the measurements, the inlet is blocked at either 25% or 50% using a plate. The block is placed at three different positions at the inlet, left side, at the middle and right side, a measurement is performed on each position and all three measurements are then averaged.

Figure 2.6: The inlet to the flume

The hollow radius of the honeycomb and the sheets was chosen to match the integral lengthscales of the flow, which was measured prior to the principal measurements. To accurately determine the water depth a gauge was placed at the outlet of the flume. The depth of the gauge was levelled against the flat section of the outlet, thereby, z=0.

Figure 2.7: The depth gauge used to measure the water height
2.3. GÄVUNDA CASE STUDY TUNNEL

Water was pumped from the outlet into an area upstream of the baffle. The water depth was regulated by an inclined plate at the outlet of the channel and was monitored using two magnetic flow meters. The particles were released just downstream of the baffle and was collected by a filter after the outlet.

2.3 Gävunda case study tunnel

The tunnel has a length of about 520 m, a typical width of 7.2 m and a height of 6.9 m. The dimensions were statistically determined by measuring over a number of cross-sections of the tunnel. The hydraulic radius is defined as

$$R_h = \frac{A_s}{P_s}, \quad (2.1)$$

where $A_s$ is the local cross-sectional area and $P_s$ is the local wet perimeter. The inlet of the tunnel has a cross-section significantly larger with respect of the rest of the tunnel, with a hydraulic radius of about 2.14 m. From the inlet, the tunnel contracts until about 60 m downstream were the average hydraulic radius of the rest of the tunnel is about 1.83 m. Until about 110 m downstream the tunnel is relatively straight, whereby the bend begins and stretches to roughly 410 meters. The pre-excavation schematics of the tunnel can be seen in Fig. 2.8.

![Figure 2.8: A top-view (left) and cut-through (right) schematic of the tunnel, both drawings made pre-excavation](image)

The vast point-cloud provided on the tunnel proved arduous to manage in a realistic way. Due to the tunnel being non-linear in all coordinates, it is problematic to isolate specific sections of the tunnel such as a wall or a section. The approach chosen here were firstly to establish a centreline of the tunnel, an example of a part of the tunnel and its corresponding centreline can be seen as the red line in Fig. 2.9 a).
CHAPTER 2. GENERAL SETUP

Figure 2.9: a) depicts a section of the tunnel, the red points are all points within 0.25 m of the perpendicular plane, the red line is the centreline of the tunnel. b) depicts the cross section resulting from averaging the red points in a)

One plane is inserted every 10 cm using the centreline as normal, ensuring that the planes are perpendicular to the flow direction. All points within 25 cm of each planes were chosen and averaged length-wise as \((x, y, z)\). Each point in each transect were then transformed to polar coordinates and thereafter angularly averaged with a span of 1 degree according to \((x_{θ}, y_{θ}, z_{θ})\). Each 10 cm section of the tunnel, as well as any given section of the walls can now be accessed. It should be noted that the bend of the tunnel is omitted during this visualization.
Experimental methods

The experimental methods applied in this thesis include PIV, PTV, ADV and pressure measurements. These methods will be further explained in this chapter.

### 3.1 Particle Image Velocimetry

PIV is a non-intrusive method used for visualisation of the flow and quantitative velocity measurements. The method employs a laser for illumination, camera for image acquisition, particles and typically require optical access from two perpendicular sides of the phenomenon studied (Raffel et al, 2013). In short, the laser is used to illuminate the particles in the fluid while the camera captures two pictures separated by a short timestep ($\Delta t \approx O(\mu s)$). The software divides the imaging plane (captured by the camera) into several sub planes, typically in the range of 32x32 pixels, thenceforth small groups of particles can be statistically traced and an instantaneous realization of the flow can be attained, see Fig. 3.1.

![Figure 3.1: Depiction of the measuring process of PIV. $t$ and $t'$ depicts the timestep between the two picture-pairs](image)

This process is repeated for a number of times sufficient to create a stable temporal average, 712 pictures in this case. The instantaneous realizations are
CHAPTER 3. EXPERIMENTAL METHODS

then averaged according to Fig. 3.2.

![Figure 3.2: The averaging process](image)

### 3.1.1 Setup

The PIV-system used is a commercially available system from LaVision GmbH which has been applied in a number of studies, including (Larsson et al, 2012). It consists of a Litron Nano L PIV laser, i.e. a double pulsed Nd:YAG with a maximum repetition rate of 100 Hz and a pulse energy of 50 mJ. A 10-bit LaVision FlowMaster Imager Pro CCD-camera with a spatial resolution of 1280 x 1024 pixels per frame is used for image acquisition. Sheet optics and mirrors produced a 1.5 mm thick laser sheet and placed it in the desired location, and a Nikon 50 mm f/1.8D lens was fitted on the camera. The laser is mounted on a traverse allowing a simultaneous repositioning of the laser sheet and camera of up to 500 mm in the x-, y- and z-directions. The traverse was not placed on the experimental setup but instead was operated independently, a precaution preventing any large loads acting on the channel and to prevent vibrations from the rig to interfere with the camera. To cover the entire measuring section the traverse needed to be repositioned between image capturing. To consider the laser sheet attenuation in the image periphery, subsequent positions are set to give a 20 mm overlap of the images. The tracer particles used were the previously proven feasible (Andersson et al, 2012) AkzoNobels Expancel 461 WU 20 hollow thermoplastic spheres with a diameter ranging from 2 μm to 30 μm, and a density of 1.2 g/cm³. The measurements were performed with a frequency of 75 Hz during 9.49 s, corresponding to a total of 712 image pairs for each recorded set. To account for the localized variations in velocity and pixel displacement, the time interval between the laser pulses ranged from 150 μs - 275 μs depending on the measuring position. The results were a typical mean displacement over the whole velocity field of 0.3 pixels in the y-direction and 7 pixels in the x-direction with a characteristic particle image diameter of 2 pixels. At approximately 490 samples the temporally averaged velocity converges towards a stable value. Beyond 560 samples the velocity differs no more than 1.5% from the converged value. The PIV measurement where performed at a plane starting at 6.8 m downstream of the channel inlet, See Fig. 2.2.
3.1.2 Postprocessing

Post-processing of raw PIV-images was carried out using the commercial software DaVis by LaVision Gmbh (2007). A min/max filter for particle intensity normalization followed by a multi-pass scheme with decreasing window size and offset was used to calculate the particle displacement. The interrogation window size was 32x32 pixels for the first pass and 16x16 pixels for the second pass with adaptive window shift, both with an overlap of 25%. The cross-correlation was performed using the standard cyclic FFT-algorithm with a three-point Gaussian peak fit to estimate the sub-pixel displacement, followed by vector post-processing by applying a median filter to reject spurious vectors (less than 2%) and to interpolate from surrounding interrogation windows (Westerweel and Scarano, 2005). The processed data were imported into Matlab using the application PIVmat where further analysis was performed. Due to limitations of the field of view of the camera and the laser power it is not possible to capture the entire measuring section in one measurement. The planes therefore had to be divided into smaller planes which was measured individually and then manually merged together. The process of merging the measured sets into one complete plane resulted in some minor discrepancies, which can be seen in some of the data. The double averaging process is performed through two decompositions, the first part is the Reynolds decomposition where $\theta = \bar{\theta} + \theta'$, $\bar{\theta}$ is the temporally averaged quantity and $\theta'$ is the quantity fluctuating in time. The second part is the spatial decomposition, $\bar{\theta} = \langle \bar{\theta} \rangle + \tilde{\theta}$ where the angle brackets denote spatial averaging over the desired plane and tilde denotes the spatial deviation from the double averaged component $\langle \bar{\theta} \rangle$. The Reynolds decomposition is applied when post-processing the raw PIV-images, while the spatial decomposition is applied a posteriori on the processed PIV images.

3.1.3 Error Estimation

A PIV experimental setup consist of several sub systems, and hence there are a number of potential error sources. The overall measurement accuracy in PIV is a combination of a variety of aspects extending from the recording process all the way to the methods of evaluation (Raffel et al, 2013). A cornerstone in all experimental design is to randomize the measuring procedure. By proper randomization, the effects of extraneous factors that may be present have less impact on the result (Montgomery, 2009). The measurement uncertainties consist of those due to systematic biased errors and random precision errors (or due to erroneous measurements) (Coleman and Steele, 1999). The biased error associated with the scaling from pixels to meters is estimated to be 0.5% as derived from measurements over a known length scale. The primary source of random error is introduced by the sub-pixel estimator in the cross-correlation. This error is estimated to be 10% of the particle image diameter, which is the diameter in pixels of the particle as seen through the camera (Balakumar et al, 2009). The mean particle image diameter in the present case is about 2 pixels, and a typical displacement between image pairs is 7 pixels in the main flow direction. Therefore the estimated random error of the measured velocity vector in each interrogation area is about 4% for the streamwise velocity component. Stitching together the domain using the measured sets may create discontinuities in the domain, due to the different sets not matching perfectly. However
CHAPTER 3. EXPERIMENTAL METHODS

by careful stitching, a good statistical convergence and choosing appropriate overlap the largest discrepancy between two sets which was no more than 1.3% in the streamwise direction. In the spanwise direction, the discrepancy is less than 1%. The rough surface reflected light from the laser which in some images saturated the camera, inhibiting measurements of the near-wall flow. However, these effects were highly localized and within $0 \leq y/h_s < 1$ of the rough surface, and hence, never affected the bulk flow. Since the rough surface was placed on a side wall of the channel, the camera was placed above the channel facing downward, see Fig. 3.1. The roughness elements closer to the camera sometimes covered parts of the plane intended for measuring, generating additional difficulties in measuring the near wall behavior of the flow.

3.2 Particle Tracking Velocimetry

PTV, sometimes referred to as low particle number density PIV, is a non-intrusive method for quantitative velocity measurements. The principle of implementation is similar as both methods determine velocity from the displacement of particles suspended in a fluid. The difference being that PIV measures mean statistical displacement of small groups of particles while PTV measures trajectories of individual particles (Dracos, 1996). The system used here consists of four cameras, floating particles, an LED ramp and a channel. The particles were black with a diameter of 21 mm, a specific weight of 0.618 g and was provided by Sinfotek. The cameras used had a resolution of 2040x2040 pixels and were roof-mounted above the channel to capture its entirety. The LED-ramp provides even illumination, enabling the camera to properly visualize the particles. To calibrate the system, four points of known position were placed in each camera’s FOV to determine the measuring domain. Since there was an overlap between the FOV of each neighboring camera, two points were placed to be common between two cameras, See Fig. 3.3.

![Figure 3.3: A visual representation of the channel with the points used in the calibration](image)

The process of calibration proved to be an arduous task, since the complete length of the channel covered by the cameras is very long. Since individual particles are measured in PTV, no even velocity profile is attained in the measuring domain. An example of a measured set can be seen in Fig. 3.4.
3.3 Acoustic Doppler Velocimetry

ADV is a measuring technique rendering all three instantaneous velocity components at a small volume (point) at relatively high frequency using coherent Doppler shift. The probe used here is a Nortek 10 MHz Velocimeter. The measuring probe consists of one transmitter and four receivers; each receiver measures data for one velocity component, hence, the w-component will have two measured sets. These two sets are averaged into one set for the actual w-component. Compared to PTV, ADV is a relatively intrusive system since the probe has to be inserted into the fluid when measuring. However, the system is flexible as it requires no laser. Usually no application of artificial seeding particles is needed, as natural seeding particles such as zooplankton, air bubbles or sediment suffice.

3.3.1 Error Estimation

The overall uncertainty in the ADV measurements can be divided into two categories, random or biased error. The random error is introduced in each
velocity estimate, this error is uncorrelated from one estimation to the next, hence, the total uncertainty can be reduced by using a large sample size. For a factory calibrated ADV this error is estimated to be less than 1% of the measured velocity. The biased error is associated with measuring e.g. close to boundaries or in strong shear layers. Due to the spatial separation between the pulse pair transmitted by the velocimeter, at a specific distance above the surface the first signal reflected from the wall will collide with the second signal inside of the measuring volume. This is called a weak spot and results in interference, an instantaneous decrease in signal to noise ratio and a unusable data point. For a flat surface the height of the weak spots can be predicted, however, the height of the surface used in this study is random and the wall will rarely be perpendicular to the incoming signal. Instead, the signal to noise ratio was monitored, and when a weak spot was identified the spatial separation between the signals was adapted accordingly to avoid this error. Monitoring of the signal also presented some problems, all bad data points had low signal to noise ratio, however, a low signal to noise ratio did not necessarily mean a bad data point. Hence, some bad points are inescapable in proximity to the rough surface, an RC-filter was applied to the data to filter away these points (Goring and Nikora, 2002). Applying filters to measured data should always be done with care as it increases the change to negatively effect the validity of the data, this was therefore applied only when unavoidable. Due to the large sample size and scarcity of spikes in the data, the points could be removed without affecting the temporal average of the data set.

3.4 Pressure measurements

Two types of pressure measurements were conducted during these experiments. 10 pressure sensors were flush mounted directly in the rough surface. The positions were chosen at extreme-points at the rough surface, such as peaks or valleys and they were all placed in an area starting from 6 to 8 meters downstream of the channel inlet, see Fig. 3.6. Additionally, 5 pressure sensors were distributed every 2 meters of the channel measuring the head loss along the surface.

![Figure 3.6: The rough surface with the positions of the flush-mounted pressure sensors marked](image)

The pressure sensors used were MTM/N10 10490 from STS, which have a measuring range of 0-10 mWC (meter water column) with an accuracy of 0.5%. All pressure sensors sampled at 200 Hz for about 40 minutes. This was repeated for a total of 5 times, between each measurement the experimental setup was
3.4. PRESSURE MEASUREMENTS

shut down and emptied of water, this was to ensure the repeatability of the experiments. The data acquisition module used in the experiments was a cDAQ-9174 chassis with a NI9025 module from National Instruments.
4
Numerical Modelling

Experimental techniques are for many applications very reliable, however, for other applications it is simply not feasible to apply them. Examples of such a restriction may be due to lack of access or a vast area of measurement. Numerical modelling is a well-established area in engineering today and a lot of trust is put into the employed software. The governing equations for fluid flow is the Navier-Stokes equation, for incompressible flows given by

\[
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial P}{\partial x_i} - \nu \frac{\partial^2 U_i}{\partial x_j^2},
\]

and the continuity equation

\[
\frac{\partial U_i}{\partial x_i} = 0.
\]

\[4.1\]
\[4.2\]

\(\rho\) is the fluid density, \(\nu\) is the kinematic viscosity, \(U_i\) is the velocity components and \(P\) is the fluid pressure. Conceptually, Direct Numerical Simulation (DNS) is the simplest numerical model since it involves directly solving Eqs. 4.1-4.2 at all ranges of motions. When applied correctly it is unrivalled in accuracy compared to other methods, but it is also the most expensive from the computational aspect. While the majority of the energy and anisotropy is contained within the larger scales of motion, the vast majority of the computational effort will be directed into the smallest dissipative scales of motion. Therefore, the computational cost of DNS increase with \(Re^3\) and the method quickly becomes difficult to use. This section will describe two methods used in this work.

4.1 Reynolds-Averaged Navier-Stokes (RANS)

The basis of RANS modelling is to apply Reynolds decomposition \(\theta = \bar{\theta} + \theta'\) to the flow parameters of Eqs. 4.1-4.2 (Pope, 2001). \(\bar{\theta}\) is the ensemble averaged component and \(\theta'\) is the fluctuations around the average. The resulting relation is the Reynolds Averaged Navier Stokes equation

\[
\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{U}_i \bar{U}_j) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_k} \left( \nu \frac{\partial \bar{U}_i}{\partial x_j} - \bar{u}_i \bar{u}_j \right),
\]

and the continuity equation

\[
\frac{\partial \bar{U}_i}{\partial x_i} = 0.
\]

\[4.3\]
\[4.4\]
CHAPTER 4. NUMERICAL MODELLING

$U_{i,j}$ is the velocity components and $P$ is the model pressure. $\overline{u_i u_j}$ is an additional term added due to the velocity fluctuations and is called the Reynolds stresses. These equations will be used to solve for the mean flow while the $k-\varepsilon$ model will be applied for turbulence closure.

4.1.1 $k-\varepsilon$ turbulence model

The $k - \varepsilon$ model is a turbulent viscosity model were the transport equations are solver for two quantities, the turbulent kinetic energy $k$ and the turbulent dissipation $\varepsilon$. The Reynolds stresses in Eq. 4.3 is estimated according to

$$\overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \nu_T \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right). \tag{4.5}$$

The Eddy viscosity $\nu_T$ in equation 4.5 is given by

$$\nu_T = \frac{C_\mu k^2}{\varepsilon}, \tag{4.6}$$

where $C_\mu$ is a model constant and $\varepsilon$ is the turbulent dissipation. Fully resolving the flow close to the wall will significantly increase the computational cost. It is therefore usual for numerical schemes to use wall functions to solve this problem, this is described in the following section.

4.1.2 Near-wall modelling

One key feature for wall turbulence is the presence of a wall imposing inhomogeneity in the flow. The no-slip boundary condition puts important constraints on the flow, hence, the scaling regularly used is made to highlight the growing relative importance of viscosity ($\nu$) and wall shear ($\tau$) in relation to the wall. From the wall shear, the friction velocity can be constructed according to $u_t = \sqrt{\frac{\tau}{\rho}}$, where $\rho$ is the density. $u_t$ is for most applications a global velocity scale and the Reynolds stresses are of the order of $u_t^2$ throughout the boundary layer. Using the friction velocity and the viscosity, a viscous lengthscale $\nu/u_t$ can be constructed. This scaling is regularly denoted by superindex $^+$.

Measuring the distance from the wall in viscous units is denoted by

$$y^+ = \frac{u_t y}{\nu}. \tag{4.7}$$

The $y^+$ value can be interpreted as a local Reynolds number and can be used as a basis to define layers within the near wall flow. At high Reynolds number close to the wall ($\frac{u_t y}{\nu} \ll 1$), the dimensionless velocity $u^+$ depends solely on the dimensionless wall distance $y^+$. In this region the mean velocity gradient is

$$\frac{du^+}{dy^+} = \frac{1}{\kappa y^+}, \tag{4.8}$$

which integrates to

$$u^+ = \frac{1}{\kappa} \ln y^+ + B^+. \tag{4.9}$$

This relation is called the logarithmic law of the wall and the method is called outer-layer similarity treatment, see Fig. 4.1. $B$ is a constant and $\kappa$ is the von
Karman constant, both constants differ depending on the application but are generally within 5% of $\kappa = 0.41$ and $B = 5.2$ (Pope, 2001).

Figure 4.1: The logarithmic law of the wall

The logarithmic law of the wall is valid in the inertial sublayer which starts at $y^+ \simeq 30$. Below $y^+ = 5$, assuming any individual roughness elements is not large enough, viscosity is the dominant effect. The flow is not steady, but the contribution of the velocity fluctuations to the total stress will be small. This region is called the viscous sublayer, within this region the velocity profile is linear, due to the negligence of the Reynolds stress. In the buffer layer, neither the viscosity or the Reynolds stresses can be neglected. This relation can significantly reduce computer cost when modelling and it has successfully been validated for many applications. As seen in this work, it is known to fail for cases of significant roughness and/or in the presence of strong pressure gradients.

4.2 Large-Eddy Modelling

In LES, Eqs. 4.1-4.2 are filtered in space by decomposing the velocity $\mathbf{U}$ according to

$$\mathbf{U}(\mathbf{x}, t) = \tilde{\mathbf{u}}(\mathbf{x}, t) + \mathbf{u}'(\mathbf{x}, t).$$

$\tilde{\mathbf{u}}(\mathbf{x}, t)$ is the resolved component and $\mathbf{u}'(\mathbf{x}, t)$ is the residual component (Pope, 2001). Applying this decomposition to the Navier-stokes equations renders the filtered Navier-stokes equations

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_i \frac{\partial \tilde{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{P}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_j}{\partial x_i \partial x_j} - \frac{\partial \tau_{ij}^r}{\partial x_i}$$

and the filtered continuity equation

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0.$$

The model filtered equations are solved numerically for $\tilde{\mathbf{u}}(\mathbf{x}, t)$ which provides an approximation to the large-scale motions in one realisation of the flow. $\tau_{ij}^r$ is the residual stress tensor, defined as

$$\tau_{ij}^r = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j.$$
CHAPTER 4. NUMERICAL MODELLING

The residual stress tensor is modelled using an eddy-viscosity approach, from which the following expression is derived

\[- \left( r_{ij} - \frac{\delta}{3} r_{kk} \right) = \nu' \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right), \]

(4.14)
Method

This chapter will present the methods used in this study. Firstly the mean flow effects seen in this work. How to characterize important length scales of the rough surface and how to generate artificial roughness. The methods of POD, Quadrant analysis and a spatial decomposition method to estimate $u_\tau$ from the pressure measurements are explained.

5.1 Implications on the mean flow

The basic assumption of outer-layer similarity treatment is that the effects of surface roughness is confined to a thin layer close to the rough surface and does not affect the main bulk of the flow (Nakagawa et al, 2003; Nakagawa and Hanratty, 2003; Seddighi et al, 2015). The consequence of this assumption is that the rough surface is treated only as friction inducing, draining the near-wall flow of momentum and thereby shifting the maximum of the double averaged velocity profile away from the rough surface. This assumption is highly accepted in the field of fluid mechanics and is a cornerstone in many of the most common CFD-models. However, research within this project has shown that its validity is highly dependent on the flow case and it is in fact incorrectly used in many applications. Velocity data from PIV-measurements can be seen in Fig. 5.1.

![Figure 5.1: Experimental data from smooth pipe data (triangle, courtesy of Joel Sundström) and rough wall data (+)Andersson et al (2018)](image)

It is clear that below half the channel, the difference between the smooth and rough wall is significant and the maximum of the velocity is actually shifted
CHAPTER 5. METHOD

towards the rough surface. This effect will be further evaluated in the Results section.

5.2 Characterizing rough surfaces

In this section, two specific methods of characterizing surface roughness will be presented as well as a method of generating artificial rough surfaces. A section will also be dedicated on how to extract desired information from point-clouds.

5.2.1 Roughness length-scales

One important factor for characterizing a rough surface is the Root Mean Square (RMS) roughness factor, which denotes the average height of the roughness elements on the surface. Height (denoted \( h \)) is defined as any instantaneous elevation measured with respect to the average surface elevation, which is set to zero. Since the mean elevation is set to 0 the RMS is equal to the standard deviation. For practical reasons, measuring head loss or boundary layer shearing \( (\Delta U^+) \) to determine the corresponding sand grain roughness factor is not a realistic option. Therefore the RMS roughness factor is calculated solely from the physical height of the surface, defined as (Sarkar and Dey, 2010; Bratveit et al, 2012)

\[
h_s^2 = \int_{-\infty}^{+\infty} h^2 p(k) dk. \tag{5.1}
\]

As mentioned, \( h_s \) is solely based on the height on the rough surface and does not take into consideration e.g. shape or aspect ratio of the roughness. To evaluate the longitudinal scale the auto-correlation function \( R(r) \) is introduced in the streamwise \( (x) \) direction of the rough surface according to (Tennekes and Lumley, 1972)

\[
R_h(r,y) = \frac{1}{h^2(x_2 - x_1)} \int_{x_1}^{x_2} h(x,y) \bar{h}(x+r,y) dx \tag{5.2}
\]

where \( r \) is the streamwise incremental coordinate and

\[
\bar{h} = \bar{h}(x,y) - \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} \bar{h}(x,y) dx = \bar{h} - \langle \bar{h} \rangle. \tag{5.3}
\]

By integration of \( R(x) \) according to Eq. 5.4 a longitudinal integral length-scale can be obtained.

\[
\zeta_r \equiv \int_0^\infty R(x) dx. \tag{5.4}
\]

Conclusively, \( h_s \) should be viewed as a quantity representative for the height of the roughness elements, while \( \zeta_r \) represent the length of the roughness elements on the surface. For the rough surface used in the PIV-measurements, \( h_s = 9.49 \) mm and \( \zeta_r = 39.1 \) mm.

5.2.2 Diamond square algorithm

For verification purposes it is important that the roughness heights are distributed randomly to ensure that the spatially averaged roughness is uniform.
5.2. CHARACTERIZING ROUGH SURFACES

With this in mind, for some cases it may prove more reliable to generate an artificial rough surface which represents the natural roughness of a given surface. Fractals have properties that are of interest for generating rough surfaces, such as self-similarity which is often observed in natural environments such as riverbeds or excavated environments such as tunnels. A method often used to generate synthetic natural terrain is the diamond square model (Fournier et al., 1982). The diamond square algorithm is a recursive sub-division algorithm. In short, a new point is added between each existing point for each iteration. Each new point added will be the average of its neighbour points plus a stochastic factor, see Fig. 5.2.

The size of the stochastic perturbation decrease with every iteration, making the added roughness elements smaller each step. Four iterations of the process can be seen in Fig. 5.3.

This algorithm was used to generate the surface used in the ADV and PTV measurements, see Sec. 2.2. This method is both numerically cheap and relatively easy to implement, for this application no more than 8 iterations of the algorithm was needed for sufficient resolution of the final surface.
CHAPTER 5. METHOD

5.3 Proper Orthogonal Decomposition

POD is an algorithm which determines and hierarchically ranks the dominant structures in the flow with respect to their energy content, allowing the statistical capture of flow structures despite eventual shortcomings such as insufficient temporal resolution and/or sample size. The POD modes stem from calculation of the singular eigenvalue decomposition

\[ R_{\text{ui}} = \lambda_i v_i \]  

of the autocovariance matrix \( R \), given by

\[ R = U^T U. \]

\( i \) is the total number of eigenvalues, \( U \) is a matrix where the columns consist of the instantaneous fluctuating velocity snapshots, according to

\[ U = \begin{bmatrix} | & | & : & | \\ u_0' & u_1' & \ldots & u_{Nt}' \end{bmatrix}, \]

where \( u_j' = u_j - \bar{u} \) for \( j = \{1, 2, \ldots N_t\} \). \( N_t \) is the number of snapshots, 712 in the current case. The modes are then calculated and normalized by

\[ \phi_i = \frac{\sum_{n=1}^{N_t} u_n' u_n}{\sqrt{\sum_{n=1}^{N_t} u_n'^2}}. \]

The method stems from Bakewell and Lumley (1967) and a more recent introduction to POD can be found in Meyer and Pedersen (2007).

5.4 Quadrant analysis

Quadrant analysis is a method to disclose the instantaneous point-contribution of the velocity fluctuations to the Reynolds stress in relation to a defined quantity \( H \), defined as

\[ H = \frac{u'v'}{u y}. \]

In short, the contribution to the Reynolds stresses is divided into one of four possible quadrants depending on the sign of the instantaneous velocity fluctuations. As \( H \) increases, low magnitudes of the instantaneous velocity products are sorted out, thus only the significant contributions are left for comparison. Naturally, quadrant 2 and 4 represent a negative product and thereby a positive production of turbulent energy, since the production \( P \) is given by

\[ P = -u'v' \frac{\partial \bar{u}}{\partial y}. \]
Accordingly, quadrant 1 and 3 represent a negative production and thereby an extraction of energy from the turbulence to the mean flow. Quadrant 2 events generally, but not always, represent ejection and similarly, quadrant 4 events represent sweeps Pope (2001). Quadrant analysis is a handy tool for identifying both the extent and magnitudes of localized disruptions within the flow and will, in this study, be used in connection to the shear layer formed at the crest of roughness elements.

5.5 Estimation of $u_{\tau}$

The wall shear stress on the rough wall $\tau_r$ can be evaluated by (Chanson, 2004)

$$\tau_r = \rho g R_r S_f,$$

where $S_f$ is the gradient of the friction line defined as $-\frac{1}{\rho g} \frac{d \rho}{d x}$. $R_r$ is the hydraulic radius with regard to the rough wall and $\rho$ is the fluid density. $\frac{d \rho}{d x}$ is derived from the head loss measurements (Andersson et al., 2016) or simulation data in the Gavunda case. In river engineering it is common practice to decompose the wetted perimeter, $P$, and the cross sectional area, $A$, into parts when properties (such as roughness) vary significantly over the considered cross section. A good review of this practice is given by Yen (2002) and one of the simpler methods dates back to Einstein (1942). Starting from the Manning equation, given by (Chanson, 2004)

$$U = \frac{1}{n} R^{2/3} S_f^{1/2},$$

where $U = Q/A$. Due to the pressure being known from the measurements, the only unknown in this equation is the hydraulic radius $R$. The rectangular cross section of the channel is decomposed into a rough and a smooth part. Using this methodology the hydraulic radius, which varies throughout the tunnel, can be expressed as

$$R_r = \frac{A}{P} = \left(2 \frac{d_r}{b} + 1\right) \left(\frac{n_s U_0}{\sqrt{S_f}}\right)^{1/2}.$$

$n_s = 0.010 \text{ s/m}^{1/3}$ represents the Manning’s number for the smooth walls (i.e. glass or plastic) of the channel (Chanson, 2004). Besides the assumption of the decomposition of $P$ and $A$, Eq. 5.13 also assumes that the pressure gradient, $S_f$, is constant for all decomposed parts. $U_0$ is the bulk flow velocity for the measurement section. This method of decomposition should be considered an approximate way of estimating the friction velocity, but it still reflects more representative conditions than just considering average values for the entire cross section (smooth and rough surfaces considered jointly).
Results and discussion

6.1 Mean flow

Studies such as Bennet and Best (1995) have shown proof for localized velocity phenomena in connection to the rough surface. One manifestation of this phenomena is the zone of high velocity formed at the crest of the ridge, positioned at \( x \approx 7.06 \) m downstream. The average bulk velocity \( U_0 \) is 1.761 m/s for the PIV and 1.836 m/s for the LES respectively.

Immediately downstream of the ridge, a zone of negative velocity can be seen in the flow field, an effect similarly visualized by Bennet and Best (1995). Similar to the previously mentioned study, the negative horizontal flow in the separation zone is about \(-0.130U_0\) for the PIV and \(-0.133U_0\) for the LES respectively, indicating severe shear drag in the separation zone. In Fig. 6.2 the double averaged velocity profiles from the PIV, LES and RANS can be seen. The asymmetric channel flow case (one rough wall opposite of a smooth one) has been well documented by Hanjalic and Launder (1972). Traditionally, the rough surface acts as a sink for momentum for the flow, and due to the outer similarity treatment the velocity close to the surface can then be approximated using the logarithmic law of the wall. Accordingly, the maximum of the double averaged streamwise velocity component is shifted away from the rough surface (Nakagawa et al, 2003).

![Figure 6.1: velocity field (\( \tau \)) for the PIV (left) and LES (right)](image-url)
Figure 6.2: The double-averaged streamwise velocity component from the PIV, LES and RANS

The agreement between the experiments, LES and RANS are very good considering the double averaged velocity. The agreement appears to be slightly better for the RANS approach, mainly due to the LES slightly over-estimating the acceleration of the flow above the roughness element.

6.2 Spatial velocity correlation

Using Eqs. 5.2-5.4 an equivalent lengthscale $\zeta$ can be derived for the each temporally averaged velocity component, rendering a quantity representative of the largest scales of motion present in the flow (Tennekes and Lumley, 1972). This operation continues from the crest (not $y/h_s = 0$) to $y/h_s \approx 8$, see Fig. 6.3. The values labeled smooth are measurements near the Plexiglas wall opposite of the rough surface in the center plane and are meant to represent a smooth wall case. These values are similar for both the upper and middle case, therefore only one the middle is displayed.

Figure 6.3: The integral length scale $\zeta$ for the $u$-component

Near the surface, the flow exhibit very different behaviour between the two planes up until about half the channel ($y/h_s \approx 8$). The middle plane show a sharp increase in the length scale at $y/h_s \approx 2.7$, about $0.37h_s$ above the
6.3. QUADRANT ANALYSIS

crest of the roughness element with a magnitude of $\zeta/\zeta_r \simeq 1.6$. The peak, to a degree, indicate the shear layer forming between the bulk and recirculation zone following the roughness peak visible in Fig. 6.1. Scaling the results with the integral length scale of the rough surface, $\zeta_r$, as done in Fig. 6.3 provides some interesting insight into the size of the flow structures. There is a strong correlation between the length scales of the rough surface and the flow above the rough surface since $\zeta/\zeta_r \simeq 1$ in the bulk flow, see Fig. 6.3. The obvious explanation for this would be that the rough surface creates similar length scales of the flow above the rough surface. Which would also suggest that the effects of the surface roughness is visible in the entire channel and not just in the vicinity of the wall, a notion proven for similar flow applications (Buffin-Bélanger et al., 2006). This is a likely hypothesis and the idea is quite intriguing, however, the extent of this phenomenon has to be further investigated before any definite conclusions can be drawn.

6.3 Quadrant analysis

Five points was chosen in connection to the ridge visible in Fig. 6.1, the exact location of the points is given by the points in Fig. 6.4.

Figure 6.4: Subsequent of the five points subject to the quadrant analysis

Point a) is placed at $\sigma_{max}$ showing an overwhelming dominance of Q2 events for all $H$, consistent with Bennet and Best (1995), indicating ejections of low velocity fluid away from the rough surface. Point b) and c) are placed relatively close to each other, both on either side of the shear layer separating the accelerating and recirculating flow. Both points show the highest measured $\overline{uv}$ magnitudes of all points, 8.41 and 7.67 $m^2/s^2$ respectively. Point b) show a similar magnitude for Q2 and Q4 for $H = 0$, however, the most dominant event for $H > 2$ is Q1. Point c), which is placed in the separation zone, show an overall dominance of Q4 events for all $H$. Which is an indicator of sweeps of high velocity fluid moving towards the wall. Points c) and e) are placed at similar heights leeward of the roughness element, thus, displaying similar behavior. The main difference being the displayed $\overline{uv}$ magnitudes which have dissipated significantly by point e). Presumably, if no other roughness element would occur downstream, Q2 events would again become dominant as similarly theorized by Bennet and Best (1995).
However, within the selected section there is no visible zone of reattachment. Surprisingly, for $H < 3$, the major contribution in point d) is $Q_3$ followed by $Q_1$. d) also has the lowest recorded measured $\vec{uv}$ magnitude for $H = 0$, which is $-0.0747 \text{ m}^2/\text{s}^2$. For larger $H$ $Q_2$ events become dominant. One possible reason for this might be traces of decelerating high velocity flow from the ridge still present where the point is located.

Figure 6.5: Instantaneous contributions to the Reynolds stresses in the points denoted in Fig. 6.4
6.4 Proper Orthogonal Decomposition

Due to the limitations in camera FOV the subsets could not be captured at the same time, hence, any perturbations in the flow could not be tracked from one subset to another and thereby limiting the visualization of the data. Using POD, the distribution of energy from each subset can be statistically ranked. The position of the area where the POD was performed is marked by the cyan box in Fig. 6.6

![Figure 6.6: Position of the area where POD was applied](image)

The subsequent three first POD-modes can be seen in Fig. 6.7

![Figure 6.7: The first three modes from the POD, the left figure is the first mode, the textboxes denote the amount of captured kinetic energy within the mode. The location of the POD is given by the cyan box in Fig. 6.4](image)

In total, 33.2% of the fluctuating velocity kinetic energy is contained within the first three modes. The modes are dimensionless and the energy content comes from the eigenvalues in Eq. 5.5. Assuming the mode ends at 20% of the maximum, a longitudinal length scale of $\zeta_{POD}/\zeta_r \approx 1.55$ can be determined, which is similar to the peak in Fig. 6.3. Although quite old, the method has been applied to surprisingly few cases. Hence, data for comparison is scarce, the results are often arbitrary from case to case and no definitive general conclusions have been drawn. However, it is clear in this case that traces from the flow interaction with the roughness element can be seen in the POD.
CHAPTER 6. RESULTS AND DISCUSSION

6.5 Pressure measurements

In order to further visualize the spatial heterogeneity of the flow, pressure sensors were mounted at points of interest along the rough surface, e.g. peaks and valleys along the surface. The complete set of pressure measurements by Andersson et al (2016) showed that although the pressure varied throughout the rough surface, the largest oscillations were measured by sensor 6, see Fig. 6.8. The positions of the pressure sensors can be found in Fig. 3.6.

Point number 6 is placed at the ridge measured using PIV (see Sec. 6.1) with an offset of about 2 cm to not modify the roughness element and influence the velocity measurements. Applying a Fourier transform to the pressure data reveals a wide peak stretching from about 6-9.5 Hz, see Fig. 6.9.

Applying the same methodology to the velocity data captured with the PIV and LES results in Fig. 6.10.
6.5. PRESSURE MEASUREMENTS

The velocity is sampled in a point slightly leeward and above the roughness element to prohibit interference of near-wall errors in measurements. Both velocity signals show a peak around 9.54 and 9.46 Hz. In spite of larger $Re$ and the difference in roughness shape, the recorded frequencies are of a similar order to those presented by Acarlar and Smith (1987). It should be noted that the sample size of the velocity signals are significantly lower than the pressure data. Using Eq. 2.1, the pressure measurements can be used to evaluate the wall shear and friction velocity $u_\tau$. The result can be seen in Tab. 6.1. The agreement between the experiments and the LES is within 2.3% and is good. The agreement using $k-\epsilon$ is however quite poor from the perspective of friction. This is mainly due to the $k-\epsilon$ model under-predicting the shear in connection to the roughness element.

Table 6.1: Results from applying Eqs. 5.11-5.13 on the experimental and simulated pressure data

<table>
<thead>
<tr>
<th>Data set</th>
<th>$U_0$ [m/s]</th>
<th>$S_f$ [-]</th>
<th>$R_r$ [m]</th>
<th>$\tau_r$ [N/m$^2$]</th>
<th>$u_\tau$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiments</td>
<td>1.761</td>
<td>0.0547</td>
<td>0.096</td>
<td>51.6</td>
<td>0.227</td>
</tr>
<tr>
<td>LES</td>
<td>1.836</td>
<td>0.0541</td>
<td>0.093</td>
<td>49.3</td>
<td>0.222</td>
</tr>
<tr>
<td>RANS($k-\epsilon$)</td>
<td>1.830</td>
<td>0.0372</td>
<td>0.078</td>
<td>28.4</td>
<td>0.169</td>
</tr>
</tbody>
</table>
6.5.1 Gävunda case study

Tunnel excavation is done with an intended ideal even form and area, in reality the finished tunnels will always have a hydraulic radius varying with length. This variation is very pronounced in Fig. 6.11 a).

Figure 6.11: a) The hydraulic radius as a function of the tunnel length, the black line represents the average. b) 45 cross sections of the tunnel, the red line represent the average cross section.

Figure 6.11 b) show 45 cross sections along the tunnel. A clear testament of the local variations in cross section, although the average cross-section is remarkably even the local variations due to roughness elements.

The head loss is sampled along a line placed at the centre of the channel going from the outlet to the inlet, see Fig. 6.12. Additionally, the static pressure is area-averaged over 30 cross sections placed in the channel.

Figure 6.12: The solid line represents the pressure measured at the centre of the channel, while the dotted line represents the ideal case with no variation in hydraulic radius. The data represented by stars is the static pressure averaged over the cross-sections.

Figure 6.13 a) show the head loss from the manning equation taking into account the instantaneous change in hydraulic radius, while Fig. 6.13 b) details the relation between hydraulic radius and head loss. To further evaluate this reasoning the localized effects of the hydraulic radius is taken into account. The
ideal case in Fig. 6.12 is calculated using Eq. 5.12, assuming constant \( R = 1.825 \) m and \( A = 48.290 \) m\(^2\). \( n \) is calculated from the measured head loss to be 0.022 and \( Q = 45 \) m\(^3\)/s, both will be assumed constant throughout this section. From Fig. 6.12 it is clear that the manning equation is a good estimation of the overall head loss through the channel. This is however dependent on the quality of the input data as the hydraulic radius \( R \) present difficulties in measuring and rarely remain constant in actual cases. Figure 6.13 a) show the head loss from the manning equation taking into account the instantaneous change in hydraulic radius, while Fig. 6.13 b) details the relation between hydraulic radius and head loss.

Figure 6.13: a) The circles represent head loss estimated using Eq. 5.12. b) The static pressure as a function of hydraulic radius, \( \rho \) represents the Pearson correlation coefficient

At about 150 m onward the variations increase with length, this coincides with larger instantaneous changes in hydraulic radius and the direction of the tunnel, this is a clear indicator of the inhomogeneity of the tunnel cross-section. The dependence between static pressure and hydraulic radius, especially for the large variations, is clearly depicted in Fig. 6.13 b).
CHAPTER 6. RESULTS AND DISCUSSION

6.6 Surface roughness correlation

Naturally, at a sufficient water height any disturbances generated by the rough surface will have dissipated before reaching the surface. The corresponding roughness height on the surface directly below each measured point is correlated with the measured velocity. This relation can be found in Fig. 6.14 for the lowest and highest depth.

![Figure 6.14: 50 cm depth (left) and 20 cm depth (right)](image)

At 20 cm depth there is a clear correlation between the fluctuating velocity and roughness height. This effect could easily be visually determined as the aberrations on the water surface were pronounced for the low-depth cases. However, at 50 cm depth, there is no apparent correlation between $u-h$ and only small ripples were seen on the water surface. To discern the remaining flow cases, the Pearson-correlation algorithm is applied to the data, as seen in Fig. 6.15.

![Figure 6.15: cross correlation between streamwise velocity component and the corresponding roughness height](image)

Figure 6.15 depicts a rapid linear decline of the $u-h$ correlation with an increase of depth, between 50 and 40 cm depth, the correlation has dropped by 71%. The 40 and 50 cm cases have similar correlation coefficients; hence, there is no clear correlation between $u-h$ already at 40 cm depth. This may also be an effect of the spatial shift of the surface perturbations relative to the rough surface, as...
the flow perturbations are transported downstream, while the correlation is performed between the roughness heights immediately below the measured point. Since the roughness is effective at dissipating flow perturbations, knowledge of the roughness may prove important when determining the inlet conditions. Figure 6.16 depict the entrance length at four different depths and 3 different inlet perturbations in each depth respectively. There is no clear difference between 40 and 50 cm depth and the alterations is likely an effect of the varying side-wall roughness rather than the bottom wall. Spurious particles tended to get trapped in vortices caused by the inlet blockage, hence the slight variations in the inlet. At 20 cm depth the effects of the bottom wall is distinct, at specific positions the flow rather resembles flow around obstacles.

Figure 6.16: (UL): 50 cm depth (UR): 40 cm depth (LL): 30 cm depth (LR): 20 cm depth. The black line represent the estimated position of the entrance length.

### 6.7 ADV-measurements

All ADV measurements where performed at a depth of 50 cm with no inlet perturbations and a flow of 0.115m³/s. Figure 6.17 depict the turbulent kinetic energy approximately at the inlet and 11.4 m downstream, which is close to the estimated entrance length.
CHAPTER 6. RESULTS AND DISCUSSION

Figure 6.17: Turbulent kinetic energy at two cross sections, 2.0 (left) and 11.4 (right) meter downstream respectively. The blue line represents the water surface.

At the inlet the cross-sectional distribution of TKE is uniform, indicating satisfactory inlet conditions. Although no roughness-flow correlation could be detected for a depth of 50 cm using the PTV, a clear spatial variability can be seen using the ADV. The largest magnitudes of TKE are positioned closest to the side walls, the maximum being $1.423 \text{jm}^{-3}$. Figure 6.18 depict a transect of the tunnel, similar to Fig. 6.17.

Figure 6.18: Turbulent kinetic energy from the centreline. The blue line represents the water surface.

The highest value of turbulent kinetic energy in the centreline is $0.613 \text{jm}^{-3}$, this is the fourth point from the top in the first row. Comparing the values to Buffin-Bélanger et al (2006) it is clear that, while the flow behaviour is consistent, the magnitudes are slightly lower in this case. This is likely an effect of the lower $Re$ applied in this study.
Conclusions and future work

In this thesis a number of experiments have been directed at discerning the effects of surface roughness, using measuring techniques to identify them or to properly model them. The work conducted yielded many interesting results, both expected and unexpected features.

From the PIV measurements the double averaged quantities showed surprising results, there is no traditional upward shift in the maximum double averaged velocity as an effect of the rough surface. This is in direct contrast with the traditional concept of surface roughness and the implications spans over areas ranging from numerical modelling to friction based equations. These effects are however not universal but only appears at high Reynolds number flows, as in the PIV-measurements. From a CFD-perspective this is hard to model, as the roughness has to be fully resolved. Additionally, the effects are not restricted to the vicinity of the rough surface but can be seen at lest 5-7 roughness lengths above the rough surface, the meshing has to be adapted accordingly. So how can the perturbations be identified? The longitudinal length-scales of the rough surface appears to be connected to the length-scales in the flow, as seen by the integral length-scales applied to the temporally averaged velocity. This relation should be further investigated. One possible method could be to render a certain amount of surfaces using the diamond-square algorithm. One of the surfaces would serve as validation using PIV, while the rest could be investigated using numerical simulations. If this relation should prove robust, then a way to identify the perturbations would be possible by analysing the rough surface, provided sufficiently resolved spatial data would be available. One approach would be to modify the law of the wall with a spatially stochastic localized increase in near-wall velocity gradients using the length scales as basis. The quadrant analysis was successfully validated and showed a thorough mapping of the turbulent kinetic energy in connection to the roughness element. This could serve as a base for the modified law of the wall, but additional roughness elements should be investigated further on.

The pressure measurements showed similar behaviour, where the level of pressure and fluctuations was strongly dependent on the position of the sensor. The frequency of the pressure measurements where successfully captured using k-ε turbulence model and LES. This is encouraging and show that pressure measurements can be a good complement to velocity measurements.

The Gåvunda case study show that the static pressure indeed was highly dependent on the hydraulic radius of the tunnel. While the local variations were
significant, the overall head loss could successfully be predicted using the man-
ing equation. Being able to predict the head loss is undoubtedly good for specific applications, it is no less a crude estimate of the actual dynamics within the tunnel.

Due to the vast size of the tunnel the advantage of using modified wall func-
tions, as discussed earlier, can’t be denied as opposed to fully resolving the roughness. Using integral length scales based on surface roughness does not appear to produce a measure that correlate well with the sampled pressure. But one should keep in mind that the pressure samples are lower than the provided roughness data. One should also take into account the known limitations of the RANS approach for similar cases, as the effects likely are under predicted. An experimental setup based on the Gävunda tunnel would be interesting. These experiment would be made for validation and would be comprised of both velocity measurements i.e. PIV and pressure measurements.

The PTV measurements was used to measure perturbations created at the inlet in increasing presence of surface roughness. The measurements show that the roughness perturbations could successfully be measured at the water surface up until approximately 10 roughness heights. Additionally, the PTV could be used to track inlet perturbations at all depths and show that the roughness indeed is effective in dispersing the perturbations. This is important when modelling the flow. When modelling river systems, the problems associated with vast domains appear as similarly discussed earlier. It is therefore quite usual to apply numerical wall functions modified for roughness. The ADV was successfully used to make sure that the conditions at the inlet were uniform and no inherent inlet perturbations affected the measurements.

From the simulations and experiments it is clear that the implications of the sur-
face roughness are significant. These effects are regularly overlooked in favour of equations or numerical schemes that are easy to use or numerically cheap. For some intents or purposes these simplifications may suffice, they are however often crude estimates where many instantaneous effects are filtered away. It is clear that the measuring methods have made significant advancements and will continue to do so. This will enable an expanse in the area of field measurements.
Division of work

**Paper A**

*Experimental Study of Head Loss over Laser scanned Rock Tunnel*

Andersson performed the experiments along with Larsson. The data was evaluated under the supervision of Larsson, Hellström and Andreasson. All authors contributed in the writing of the article.

**Paper B**

*Characterization of flow structures induced by highly rough surface using particle image velocimetry, proper orthogonal decomposition and velocity correlations*

Andersson performed the experiments along with Larsson. The data was evaluated under the supervision of Larsson, Hellström and Andersson. All authors contributed in the writing of the article.

**Paper C**

*Localized roughness Effects in non-uniform hydraulic waterways*

Andersson performed the simulations with the help of Burman under the supervision of Hellström. The data was evaluated under the supervision of Larsson and Hellström. All authors contributed in the writing of the article.

**Paper D**

*Inlet blockage effects in a free surface channel with artificially generated rough walls*

Andersson performed the experiments with the help of Burman under the supervision of Andreasson. The data was evaluated by Andersson with the help of Burman. All authors contributed in the writing of the article.
CHAPTER 7. CONCLUSIONS AND FUTURE WORK

Paper E

Gävunda: A case study
L.R. Andersson, J.G.I. Hellström, P. Andreasson and T.S. Lundström

Andersson performed the simulations under the supervision of Hellström. All authors contributed in the writing of the article.


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Part II

Appended articles
Experimental Study of Head Loss over Laser scanned Rock Tunnel

Authors:

Article published in:
6th International Symposium on Hydraulic Structures Proceedings, 2016, Open access
Experimental Study of Head Loss over Laser scanned Rock Tunnel

L. R. Andersson  
Lulea University of Technology, robin.andersson@ltu.se

I. A.S. Larsson  
Lulea University of Technology

J. G.I. Hellstrom  
Lulea University of Technology

P. Andreasson  
Lulea University of Technology

A. G. Andersson  
Lulea University of Technology

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Recommended Citation
Experimental Study of Head Loss over Laser Scanned Rock Tunnel

L.R. Andersson¹, I.A.S. Larsson¹, J.G.I. Hellström¹, P. Andreasson¹,² and A.G. Andersson¹

¹Div. of Fluid & Experimental Mechanics
Luleå University of Technology
Luleå
Sweden

²Vattenfall Research and Development
Vattenfall AB
Älvkarleby
Sweden

E-mail: robin.andersson@ltu.se

ABSTRACT

Flow in hydropower tunnels is characterized by a high Reynolds number and often very rough rock walls. Due to the roughness of the walls, the flow in the tunnel is highly disturbed, resulting in large fluctuations of velocity and pressure in both time and space. Erosion problems and even partial collapse of tunnel walls are in some cases believed to be caused by hydraulic jacking from large flow induced pressure fluctuations. The objective of this work is to investigate the effects of the rough walls on the pressure variations in time and space over the rock surfaces. Pressure measurement experiments were performed in a 10 m long Plexiglas tunnel where one of the smooth walls was replaced with a rough surface. The rough surface was created from a down-scaled (1:10) laser scanned wall of a hydraulic tunnel. The differential pressure was measured at the smooth surface between points placed at the start and end of the first four 2 m sections of the channel. 10 gauge pressure sensors where flush mounted on the rough surface; these sensors measure the magnitude and the fluctuations of the pressure on the rough surface. The measurements showed significant spatial variation of the pressure on the surface. For example, sensors placed on protruding roughness elements showed low gauge pressure but high fluctuations. The differential pressure indicated a head loss through the tunnel that was almost four times higher than a theoretical smooth channel.

Keywords: Pressure measurements, rough surface, hydropower-tunnel, laser scan, friction factor.

1. INTRODUCTION

Tunnels are often used when transporting water to or from hydropower turbines. In many cases, these tunnels have to be excavated through solid rock, a process which often leads to the occurrence of very large protruding roughness elements on the walls of the tunnels. These roughness elements considerably modify the local cross-sectional area of the tunnel in a more or less stochastic manner. The dynamic action of flow in such tunnels creates disturbances in the flow (Krogstad & Antonia, 1999), (Nakagawa, et al., 2003), (Kruse, et al., 2006) manifesting in, for instance, large pressure variations along the walls of the tunnel; i.e. the rock surfaces are exerted to local net destabilization forces. These forces are likely to contribute to events such as erosion or even partial collapse of the tunnel. These events may, in most applications, be difficult to predict and also hard to detect once they happen. The only indicator of a collapsed tunnel in a hydropower plant may be a substantial drop in turbine efficiency. One method applied with the aim to reduce the destabilizing forces is to “smoothen” the surface and, thus, make it more durable (Barton, et al., 1974); this can be done by spraying concrete on the wall, i.e. shotcreting (Austin & Robins, 1995). The roughness elements of rock tunnels could be considered to be self-similar and random (Perfect, 1997); however, the nature of the roughness elements differ depending on the method used when excavating the tunnel. Rock blasting a tunnel is a rapid method compared to utilizing tunnel boring machines but gives rise to periodic features of the tunnel where large roughness elements of similar size might occur at recurring intervals in the tunnel. These features inhibit the flow, increase the head loss due to friction, and increase the strain on the walls (Andersson, et al., 2012). There might also be new requirements on the tunnels and the operating conditions with the introduction of intermittent energy sources on the market with the demand on the hydropower industry to handle more transient...
flow conditions. The purpose of this experiment is to evaluate the pressure fluctuations of a hydro-power tunnel and to determine the effects of wall roughness on the pressure distribution with respect to parameters of wall roughness.

2. EXPERIMENTAL SETUP

The experimental setup consists of a closed-loop water system with a 10 m rectangular Plexiglas channel having one rough surface, a pump, two tanks placed on different levels, and pressure sensors. The high level upstream tank provides a stable driving flow through the tunnel and is connected through a 90° bend with a honeycomb placed at the entrance of the channel to straighten the flow. The honeycomb is 50 mm thick and has a cell diameter of 10 mm. In addition, three guide vanes are mounted inside of the bend to reduce secondary flow effects. The channel is 10 m long to allow the flow to be developed when it reaches the measuring section placed 6 m downstream of the honeycomb. Additionally, the channel is divided into five sections with a height of 200 mm, length of 2000 mm, and a width of 250 mm. The rough surface has an average height of 60 mm and is placed on the left wall in the flow direction of the channel, making the average cross sectional area of each section 250x140 mm². The water is collected in the second, downstream tank placed in level with the channel before it is pumped back up to the high-level tank. The flow is controlled with a PID regulator and manual valves and monitored with a flow meter. A schematic of the flow can be seen in Figure 1 where the channel has been mirrored for visual purposes; in the setup, the rough surface is placed on the left wall in the flow direction.

![Figure 1. Schematic of the experimental setup used in the campaign, the measuring section started 6 m downstream of the honeycomb, the flow in the figure is from right to left](image)

As mentioned, one sidewall of the tunnel was replaced with a rough surface model (Figure 2). The rough surface is based on a real surface that was captured by a high resolution laser scanning of a rock tunnel, a method that has been proven to be efficient for determining surface roughness (Bråtveit, et al., 2012). The laser scanning was conducted at a resolution of approximately 200 points/m². A side wall of the tunnel was extracted and scaled to 1:10 in size; the resulting model is a surface of 250x2000 mm² that has an RMS roughness factor of 9.4 mm. The difference between the highest and lowest point on the surface is 56 mm. A right-handed coordinate system is implied throughout this study. The x-axis is directed along the main flow direction with zero at the honeycomb, the y-axis is directed perpendicular to the lower wall pointing upwards, and the z-axis is perpendicular to the rough surface.

Pressure sensors were flush mounted in both the measuring section of the rough surface and every 2 m of the lower channel wall. In the rough surface, the pressure sensors are positioned to represent peaks and valleys of the rough surface (Figure 4). The coordinates for the pressure sensors can be found in Table 2. The differential pressure sensors were placed on the lower smooth surface on the tunnel. From the differential pressure sensors, it was possible to capture the total head loss over the channel as well as the head loss over specific sections of the channel.
A total of 14 pressure sensors were used in the experiments, 10 pressure sensors in the measuring section and 4 differential pressure sensors. Each differential pressure sensor measures the difference in pressure between two points located at the wall in the inlet and outlet of each of the first four 2 m sections. The pressure sensors used were MTM/N10 104490 from STS, which have a measuring range of 0-10 mwc (meter water column) with an accuracy of ±0.5%. During the experiments, a sampling frequency of 200 Hz was used; all measurements ran between 40-50 minutes and were repeated five times. The magnetic flow meter used was an IFS4000 from Krohne connected to an IFC 110 signal converter. The data acquisition module used in the experiments was a cDAQ-9174 chassis with a Ni9025 module from National Instruments.

![Image](image.png)

Figure 2. The rough surface channel; the pressure gauges can be seen just upstream of the downstream tank.

The flow through the channel is pressure driven; the head is adjusted by regulating the water level in the upstream tank placed before the channel inlet (Figure 3), and the water level is regulated by a valve placed under the upstream water tank. The flow rate was regulated by adjusting the pump connected to the loop; the pump was controlled by a PID-regulator (Figure 3), which was connected to a magnetic flow meter. The flow was approximately 63 liters per second ($Re \approx 200000$) and differed about ±4% throughout the measured sets.
The upstream water tank was also used when calibrating the pressure sensors. During the calibration, the outlet of the channel was closed and the water level inside of the tank was kept steady at a few different values allowing the pressure sensors to be calibrated. The date and time for each measurement is shown in Table 1, the measurements will follow this denotation throughout the paper.

### Table 1. The dates and denotation for each measured set

<table>
<thead>
<tr>
<th>Date</th>
<th>Denotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20150602-095023</td>
<td>Set 1</td>
</tr>
<tr>
<td>20150602-130400</td>
<td>Set 2</td>
</tr>
<tr>
<td>20150602-155523</td>
<td>Set 3</td>
</tr>
<tr>
<td>20150603-092302</td>
<td>Set 4</td>
</tr>
<tr>
<td>20150603-124918</td>
<td>Set 5</td>
</tr>
</tbody>
</table>

### 3. RESULTS AND DISCUSSION

The measuring campaign was conducted over two days. All units of pressure are in meter water column [mwc], which will furthermore be denoted as [m]. The head provided by the water tank was kept constant at approximately 3 m. A summary of the measurements can be found in Table 2. The rough surface is placed on one of the side walls of the channel, and, thereby, the height of the pressure sensors differ; this means that the sensors are submitted to different magnitudes of static pressure. These heights can be seen in the sixth column of Table 2. This effect has been adjusted for by subtracting the height of the sensors from the gauge pressure.

### Table 2. Summary of the pressure measurements; the third column($\sigma$) is the standard deviation at each point, $z$ denotes the height above or below the mean height of the roughness elements, the chevrons denote the temporal mean

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Mean Pressure [m]</th>
<th>$\sigma$ [m]</th>
<th>$\langle p_{\text{max}}-p_{\text{min}} \rangle$ [m]</th>
<th>$z$ [m]</th>
<th>$y$ [m]</th>
<th>$x$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3098</td>
<td>0.0295</td>
<td>0.3083</td>
<td>0.0081</td>
<td>0.1210</td>
<td>6.285</td>
</tr>
<tr>
<td>2</td>
<td>0.4435</td>
<td>0.0248</td>
<td>0.2410</td>
<td>-0.0049</td>
<td>0.1047</td>
<td>6.490</td>
</tr>
<tr>
<td>3</td>
<td>0.2520</td>
<td>0.0272</td>
<td>0.2673</td>
<td>0.0103</td>
<td>0.1828</td>
<td>6.629</td>
</tr>
<tr>
<td>4</td>
<td>0.2812</td>
<td>0.0250</td>
<td>0.2399</td>
<td>0.0120</td>
<td>0.0992</td>
<td>6.635</td>
</tr>
</tbody>
</table>
### 3.1. Mean Pressure

In Figure 4, the placement of the pressure sensors on the rough surface are visualized along with one pressure time series. The highest mean pressure can be found in sensors 2, 5, and 7, which are located in valleys on the surface. The high pressure in these zones indicates that there is a loss of velocity in that area due to the sudden decrease of surface elevation, which is to be expected.

![Figure 4. Pressure sensors and the corresponding measured pressure over time, the red lines denotes the average](image)

The results from all five measurements are averaged for each pressure sensor (Figure 5). The figure shows both the amplitudes of the fluctuations and the spread of the averages for each measurement at each point. The difference between each measurement is at most $\approx 10\%$, which occurs for sensor 9, while the difference for sensor 6 is only $\approx 3\%$. This shows that the setup in general is insensitive in the sense of reproducing the same conditions during several measurements.
Figure 5. The average pressure in the pressure sensors for all five measurements

The apparent spatial variation in pressure indicates that net forces act on the surface that is not necessarily perpendicular to the main direction of the wall. The largest pressure fluctuations along with the lowest pressure magnitude can be found in position number 6.

Figure 6. Comparison between pressure point 5 (left) and 6 (right) with the surface profile (top), a measured set (bottom), the standard deviation and the pressure magnitude. The flow goes from left to right.

From Figure 6, it is clear that the gauge pressure is higher in position 5 as compared to position 6. The measurement in sensor 6 shows a higher standard deviation of the pressure than in sensor 5. This can be interpreted as a higher production of turbulence in that position and that there might be some flow separation occurring. Additionally, the distance between these points is merely 166 mm. However, there is evidently a considerable difference in average static pressure and fluctuating pressure. It is not surprising that point 6, which is located on a roughness peak, displays larger fluctuations due to the vorticity generated at the roughness peak; however, the reason for displaying lower average pressure remains to be investigated.

3.2. Differential Pressure

The differential pressure was sampled at the same frequency as the gauge pressure. The differential pressure sensors were placed so that the differential pressure was measured as the difference between the inlet and outlet of each 2 m
section. The total average head loss over the channel is 0.24 m. The measurements from each set of data on each pressure sensor can be found in Figure 7.

Figure 7. The head loss over the 4 first sections from the entrance of the channel

In the first two sections of the channel, there is some deviation between the differential pressures recorded between the sets; this effect may be due to the valve located under the water tank upstream of the channel. The valve had to be slightly adjusted between the sets and definitely had an impact on the flow at the inlet. However, those discrepancies diminish further downstream in the channel, which points to the conclusion that the perturbations from the valve are small, and the flow is developed in the 4-6 m section and, hence, in the measurement section (6-8 m). One would expect the differential pressure to diminish and approach a constant value throughout the channel, but instead, the differential pressure seems to increase throughout the channel. The reason for this is unclear, and it needs to be further investigated.

The head loss inside the channel can, to an order of magnitude, be estimated and compared to a theoretical smooth channel by using the Darcy-Weissbach equation (Cengel & Cimbala, 2014):

\[
\Delta p = f \frac{L \rho V^2}{2D}
\]

where \( L \) is the length of the channel, \( V \) is the mean flow velocity, \( D \) is the hydraulic diameter of the tunnel, and \( f_d \) is the friction factor. We replace \( D \) with 4 times the hydraulic radius. The friction factor \( f_d \) can be evaluated by using the Colebrook-White equation:

\[
\frac{1}{\sqrt{f_d}} = -2 \log \left( 2.51 \left( \frac{1}{4 \sqrt{f_d}} + \frac{1}{3.7 \delta} \right) \right)
\]

assuming the sand grain roughness factor \( k_s \) to be the RMS roughness height of the surface. This is, however, a rough estimate since some of the roughness elements are significantly larger than the RMS value; hence, the flow around the largest roughness elements rather resembles flow around objects than flow over a uniformly rough surface. The results from the estimation can be found in Table 3.

Table 3. The head loss and friction factor for the experiment

<table>
<thead>
<tr>
<th></th>
<th>Smooth surface</th>
<th>Measuring section</th>
<th>Darcy-Weissbach</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta p [m] )</td>
<td>0.028</td>
<td>0.109</td>
<td>0.139</td>
</tr>
<tr>
<td>( f [-] )</td>
<td>0.015</td>
<td>0.0582</td>
<td>0.0733</td>
</tr>
</tbody>
</table>

The Darcy-Weissbach equation estimates the head loss and the friction factor about 20% higher than the actual measured pressure.
3.3. Conclusions

Pressure measurements of the flow over a rough surface were performed in a downscaled model of a laser-scanned hydraulic tunnel at a Reynolds number of about 200 000. The pressure fluctuations and the wall friction play a crucial role in a number of flow induced effects, such as erosion and hydraulic jacking. These effects are hard to predict, and, therefore, accurate measurements are valuable. The study revealed a range of mean pressures and pressure fluctuations depending on location of the sensor. The largest magnitude of the average pressure was found in the valleys of the rough surface. The largest pressure fluctuations were found in sensors located at peaks of the surface; this can be an effect of vorticity generated at the roughness elements. From the data, it is clear that the pressures in the channel have a very high spatial variance; pressure sensors positioned relatively close to each other displayed different magnitudes and fluctuations of pressure. This indicates that the net forces acting on the rough surface are not uniform and may have a destabilizing effect on sections of the tunnel walls. Decreasing the size of the protruding elements is therefore of interest when excavating rock tunnels. Differential pressure sensors were mounted along the entire length of the channel, enabling measurement of the head loss over the channel. The differential pressure sensors showed a significant increase of the head loss comparing the first and last measured section of the channel. Assuming the RMS roughness height of the surface to be the sand grain roughness factor, the head loss could (to an order of magnitude) be estimated using the Darcy-Weissbach equation. The head loss and the friction factor in the channel is about four times higher than in a theoretical smooth channel with similar dimensions, which indicates that the rough surface has a substantial effect on the flow.

4. ACKNOWLEDGEMENTS

The research presented was carried out as a part of "Swedish Hydropower Centre - SVC". SVC has been established by the Swedish Energy Agency, Elforsk, and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology, and Uppsala University. www.svc.nu.

5. REFERENCES

Characterization of flow structures induced by highly rough surface using particle image velocimetry, proper orthogonal decomposition and velocity correlations

Authors:

Article published in:
Engineering, 2018, Volume 10, Open access
Characterization of Flow Structures Induced by Highly Rough Surface Using Particle Image Velocimetry, Proper Orthogonal Decomposition and Velocity Correlations

L. R. Andersson¹, I. A. S. Larsson¹, J. G. I. Hellström¹, P. Andreasson¹, ², A. G. Andersson¹, T. S. Lundström¹

¹Division of Fluid and Experimental Mechanics, Luleå University of Technology, Luleå, Sweden
²Vattenfall Research and Development, Älvkarleby, Sweden

Email: robin.andersson@ltu.se


Abstract
High Reynolds number flow inside a channel of rectangular cross section is examined using Particle Image Velocimetry. One wall of the channel has been replaced with a surface of a roughness representative to that of real hydropower tunnels, i.e. a random terrain with roughness dimensions typically in the range of ≈10% - 20% of the channels hydraulic radius. The rest of the channel walls can be considered smooth. The rough surface was captured from an existing blasted rock tunnel using high resolution laser scanning and scaled to 1:10. For quantification of the size of the largest flow structures, integral length scales are derived from the auto-correlation functions of the temporally averaged velocity. Additionally, Proper Orthogonal Decomposition (POD) and higher-order statistics are applied to the instantaneous snapshots of the velocity fluctuations. The results show a high spatial heterogeneity of the velocity and other flow characteristics in vicinity of the rough surface, putting outer similarity treatment into jeopardy. Roughness effects are not confined to the vicinity of the rough surface but can be seen in the outer flow throughout the channel, indicating a different behavior than postulated by Townsend’s similarity hypothesis. The effects on the flow structures vary depending on the shape and size of the roughness elements leading to a high spatial dependence of the flow above the rough surface. Hence, any spatial averaging, e.g. assuming a characteristic sand grain roughness factor, for determining local flow parameters becomes less applicable in this case.

Keywords
CFD, Validation, Hydraulic Roughness, PIV, Hydropower
1. Introduction

Water tunnels are frequently used to convey water to and from hydropower turbines and in other sectors of infrastructure. The tunnels are often a key part of the design and their durability is vital for the continued operation. Tunnel excavation by rock-blasting is a relatively swift, and therefore popular, method compared to using tunnel boring machines [1]. One significant drawback of the method would be that the resulting walls of the tunnels have varying cross section and considerable surface roughness [2]. The scales of roughness in unlined hydropower tunnels range from a few millimeters to meters, which may be in the range of ≈10% - 20% of the hydraulic radius. A likely treatment of rough walls by today’s industrial standards is to estimate the roughness from the actual physical features of the roughness, e.g. estimates according to Manning, Chezy, grain size distribution [3]. These approaches have a long track record but only provide spatially averaged quantities and nothing about the actual dynamics within the tunnel. The physics of the flow in highly rough tunnels includes large variations and gradients of pressure [4] and velocity [5], resulting in intermittent pressure forces and increased local shearing load acting on the walls of the tunnel. Such forces may very well jeopardize the structural integrity of the walls, causing events including erosion or even partial collapse of the tunnel [6]. Collapsing hydropower tunnels is a known problem and documented cases show that even after 30 - 40 years of usage some tunnels have experienced sudden severe failure [7]. The connection between the details of the flow and fatal failure of tunnels is not completely understood, but it has been theorized that intermittent pressure fluctuations directly coupled to surface roughness may have induced or facilitated the process. Similar results were presented in a recent study by [8], showing that pressure-driven cyclic injection of fluid into rock material leads to larger damage, and at lower pressure than by static injection. Hydropower tunnels are a very hostile environment to measure within, hence, accurate results are almost non-existing. Capturing the geometry of existing tunnels also presents several problems: The tunnels themselves are dark and humid, making accurate measurements difficult [1]. Closing down the tunnels, and thereby any machinery operating downstream, is very expensive and puts the system in danger [6]. Therefore, there exist very few cases where experiments have been performed on models reflecting actual tunnels. This problem was highlighted by [9] but to a degree still remain today.

It is well established that rough walls modify the behavior of the flow [10], [11] however to what extent has been thoroughly debated. For rough surfaces, the turbulence is associated with shear layers formed at the crests of the roughness elements where flow separation may occur [12]. For surfaces of sufficiently large roughness, individual surface aberrations frequently penetrate into the inertial sublayer [13] [14] leading to a breakdown of the logarithmic law of the wall. Yet to this day, a common way to model flow in hydropower tunnels in industry is to replace the natural roughness with numerical wall-roughness functions. This method relies on the conventional concept that roughness effects
are confined to the inertial sublayer near the surface and have no direct effect on
the outer flow [15], a theory which for some flow cases have been questioned
[16] [17]. Many studies have been directed at the understanding of flow hetero-
geneity over rough surfaces. Measurements by [18] and [19] provided proof of
the localized velocity perturbations connected to the rough surface. This study
generally has significantly higher Re and larger roughness elements (relative to
the hydraulic radius) as compared to the mentioned studies, however, this is an
applied study and the results serve well for comparison. A study by [4] employed
flush mounted pressure sensors at points of interest, such as peaks and valleys, at
the rough surface. Sensors placed on peaks revealed elevated frequencies of the
pressure fluctuations as compared to those placed in valleys and there were a
large variation in the pressure magnitude as a function of the spatial coordinates.
The present study, which is carried out in the same channel as in [4], will com-
plement the previous study by further analysis using PIV. The scope of this ar-
ticle will be the following: 1) To further visualize the events surrounding singular
roughness elements in order to assess the current industrial evaluation standards
of uniform roughness treatment. 2) To visualize the spatial heterogeneity con-
ected to the rough walls of the tunnel. 3) To bridge the gap between flow in
hydropower tunnels and other fluvial flows. Due to the large-scale and random-
ness of the surface roughness, local flow patterns are unpredictable both spatially
and temporally. Applying only temporal averaging for the analysis of the flow
may, therefore, provide misleading results. Adding a spatial averaging to a plane
parallel to the mean flow may filter away the smallest perturbations due to e.g.
laser reflections or insufficient boundary layer resolution, while accounting for
the largest events such as flow separation. This technique is called double aver-
aging [20]. To identify the flow structures created from the rough surface inte-
ruction, the PIV-data is analyzed using proper orthogonal decomposition
(POD).

2. Experimental Setup

The experimental setup consisted of a closed loop water system with a 10 m long
rectangular Plexiglass (PMMA) channel having one rough surface, a pump, an
electromagnetic flow meter, two tanks placed on different levels and a
PIV-system. The function of the tank placed upstream of the channel is to pro-
vide a constant head on the system and to avoid air entrainment inside the
channel. A schematic of the experimental setup can be seen in Figure 1 (not to
scale).

A detailed description of the setup can be found in [4]. The flow rate was ap-
proximately 62 l/s which varied with approximately 4% throughout the cam-
paign. This corresponds to a Reynolds number of $Re = y U_e / 2\nu = 200,000$, where $y/2$ is the channel half-height, $U_e$ is the bulk velocity and $\nu$ is the vis-
cosity. The channel has a depth of 0.145 m and a width of 0.25 m. The measur-
ing section, represented by the red box in Figure 1, is positioned about 6.8 m
downstream of the tunnel inlet and has a length of 0.48 m. Figure 2 depicts the
Figure 1. The setup used in the experimental campaign. The channel along with the laser setup have been mirrored in this figure to provide a more apprehensible overview of the setup.

Figure 2. The rough surface in the measuring section, (a), the two coloured lines mark the position of the two measured planes also depicted in (b). The colour of the surface represents the relative slope of the surface topography. The flow is from left to right in the figure.

section of the rough surface over which the flow was measured during the experiments. One measuring plane was placed in the center of the channel (denoted middle), while another was placed closer to the camera (denoted upper). The color of the surface represents the slope of the surface topography and the two colored lines mark the position of the two measured planes. As can be seen in
the figure, a ridge is passing through both measuring planes at \( x = 7.06 \) m. The ridge is of interest for the measurements since the maximum height relative to \( y = 0 \) (the mean height) is similar for the two lines, additionally, the gradient of the surface is also nearly the same. However, the relative size of the ridge differs significantly between the lines. For the blue line defining the middle plane, the final slope of the ridge is very sharp but the roughness leading up to the element is relatively small, consequently, the relative size of the roughness element is small. On the red line (upper plane), the ridge is preceded by a “valley”, making the relative height larger. Ideally, four rough walls would have been used to keep the setup as realistic as possible. However, PIV requires optical access from at least 2 directions and therefore only one rough wall was used.

In this study, a right-handed coordinate system is employed with the \( x \)-coordinate (\( u \)-velocity component) originating from the tunnel entrance pointing in the flow direction. The \( y \)-coordinate (\( v \)-velocity component) is perpendicular to the rough surface with \( y = 0 \) defined as the average elevation of the surface. Accordingly, the \( z \)-coordinate originates from the bottom wall in the flow direction.

2.1. The Rough Surface Model

The rough surface model used in the experiments is a 1:10 scale side wall of an existing rock tunnel whose topography has been captured by high resolution laser scanning, a method which has been proven efficient for determining surface roughness [1]. One of the main characteristics used to describe a rough surface is the height distribution function \( p(k) \), in this case the Gaussian distribution. The meaning of \( p(k) \) is that the probability of any surface height between \( k \) and \( k + dk \) is \( p(k) \, dk \) [21]. Another important factor for characterizing a rough surface is the root mean square (RMS) roughness factor, which describes the average elevation of the roughness elements on the surface. In the current study the RMS roughness factor is denoted as the equivalent sand grain roughness factor \( k_s \) for the surface and is defined as [1] [22]

\[
k_s^2 = \int_{-\infty}^{\infty} h^2 \, p(h) \, dh.
\]

As mentioned, \( k_s \) is solely based on the height on the rough surface and does not take into consideration e.g. shape or aspect ratio of the roughness. To evaluate the spatial difference, the auto-correlation function \( R(r) \) over a specified length \( L \) is introduced in the stream wise direction (\( x \)-direction) of the rough surface [21]. The result can be seen in Figure 3, which is a \( z \)-direction average of the autocorrelation function.

Integrating the auto-correlation function according to Equation (2) produces the integral length scale of the surface

\[
r_i = \int_0^L R(x) \, dx.
\]

Conclusively, \( k_s \) is a quantity representative for the roughness height while
\( \tau \) represent the roughness length of the surface. Using Equation 1, \( k \) is determined to 9.4 mm, while \( \tau \) is found to be 39.1 mm using Equation 2. Hence, \( k \) is about 6.4% of the hydraulic radius, which can be compared to the largest global roughness elements being about 20% of the hydraulic radius. The difference is a clear indicator of the spatial heterogeneity of the rough surface used in this study. For additional numerical comparison, the relative height of the ridge in the middle plane is about 9.44 mm, which is very close to \( k \). One can hereby conclude that the ridge studied is a fitting representation of the roughness of the entire surface. Additionally, the ridge in question is far from unique on the surface but appears at regular intervals, therefore, the sample size is deemed large enough to be spatially independent.

2.2. PIV-Setup and Error Estimation

The PIV-system used is a commercially available system from LaVision GmbH which has been applied in a number of studies, including [23]. It consists of a Litron Nano L PIV laser, i.e. a double pulsed Nd: YAG with a maximum repetition rate of 100 Hz and a pulse energy of 50 mJ. A 10-bit LaVision Flow Master Imager Pro CCD-camera with a spatial resolution of 1280 × 1024 pixels per frame is used for image acquisition. Sheet optics and mirrors produced a 1.5 mm thick laser sheet and directed it to the desired location, and a Nikon 50 mm f/1.8 D lens was fitted on the camera. The laser was mounted on a traverse allowing a simultaneous repositioning of the laser sheet and camera of up to 500 mm in the \( x \), \( y \), and \( z \)-directions. The traverse was placed and operated independently of the experimental setup, a precaution preventing any large loads acting on the channel and to prevent vibrations from the rig to interfere with the camera. To cover the entire measuring section the traverse needed to be repositioned between image capturing. Accordingly, the planes had to be divided into 14 (middle) and 24 (upper) smaller subsets which were measured individually and then manually merged together. The spatial dimensions of each subset are about 100 mm (\( x \)-direction) by 80 mm (\( y \)-direction). To consider the laser sheet attenua-
tion in the image periphery, subsequent positions are set to give a 30 mm overlap of the images. Stitching together the domain using the measured sets may create discontinuities in the domain, due to the different sets not matching perfectly. However by careful stitching, a good statistical convergence and choosing appropriate overlap the largest discrepancy between two sets which was no more than 1.3% in the streamwise direction. In the spanwise direction, the discrepancy is less than 1%. The tracer particles used were the previously proven feasible [24] Akzo Nobels Expancel 461 WU 20 hollow thermoplastic spheres with a diameter ranging from 2 μm to 30 μm, and a density of 1.2 g/cm³. The measurements were performed with a frequency of 75 Hz during 9.49 s, corresponding to a total of 712 image pairs for each recorded set. To account for the localized variations in velocity and pixel displacement, the time interval between the laser pulses ranged from 150 μs - 275 μs depending on the measuring position. The results were a typical mean displacement over the whole velocity field of 0.3 pixels in the y-direction and 7 pixels in the x-direction with a characteristic particle image diameter of 2 pixels. At approximately 490 samples the temporally averaged velocity converges towards a stable value. Beyond 560 samples the velocity differ no more than 1.5% from the converged value. A PIV experimental setup consists of several sub systems, and hence there are a number of potential error sources. The overall measurement accuracy in PIV is a combination of a variety of aspects extending from the recording process all the way to the methods of evaluation [25]. A cornerstone in all experimental design is to randomize the measuring procedure. By proper randomization, the effects of extraneous factors that may be present have less impact on the result [26]. The measurement uncertainties consist of those due to systematic biased errors and random precision errors (or due to erroneous measurements) [27]. The biased error associated with the scaling from pixels to meters is estimated to be 0.5% as derived from measurements over a known length scale. The primary source of random error is introduced by the sub-pixel estimator in the cross-correlation. This error is estimated to be 10% of the particle image diameter, which is the diameter in pixels of the particle as seen through the camera [28]. The mean particle image diameter in the present case is about 2 pixels, and a typical displacement between image pairs is 7 pixels in the main flow direction. Therefore the estimated random error of the measured velocity vector in each interrogation area is about 4% for the streamwise velocity component. The rough surface reflected light from the laser which in some images saturated the camera, inhibiting measurements of the near-wall flow. However, these effects where highly localized and within 0 ≤ y/δ < 1 of the rough surface, and hence, never affected the bulk-flow. Since the rough surface was placed on a side wall of the channel, the camera was placed above the channel facing downward, see Figure 1. The roughness elements closer to the camera sometimes covered parts of the plane intended for measuring, generating additional difficulties in measuring the near wall behavior of the flow. The laser sheet was initially positioned at the center of the channel (middle plane) to get a measurement where the effect of the side walls was as
small as possible, and to get a measurement over a distinct roughness element. The second measurement section (upper) was placed at the same x-coordinate as the first one but closer to the camera, see Figure 2.

2.3. PIV Post-Processing

Post-processing of the PIV-data was done using the commercial software DaVis by LaVision [29]. To calculate the particle displacement, a min/max filter for particle intensity normalization followed by a multi-pass scheme with decreasing window size and offset was used. The interrogation window size was 32 × 32 pixels for the first pass and 16 × 16 pixels for the second pass with adaptive window shift, both with an overlap of 25%. The cross-correlation was performed using the standard cyclic FFT-algorithm with a three-point Gaussian peak fit to estimate the sub-pixel displacement, followed by vector post-processing by applying a median filter to reject spurious vectors (less than 2%) and to interpolate from surrounding interrogation windows [30]. The processed data were imported into Matlab using PIV mat where further analysis was performed. The double averaging process is performed through two decompositions, the first part is the Reynolds decomposition where \( \bar{\theta} = \bar{\theta} + \theta' \). \( \bar{\theta} \) is the temporally averaged quantity and \( \theta' \) is the quantity fluctuating in time. The second part is the spatial decomposition, \( \tilde{\theta} = \langle \tilde{\theta} \rangle + \theta' \) where the angle brackets denote spatial averaging over the desired plane and tilde denotes the temporal deviation from the double averaged component \( \langle \tilde{\theta} \rangle \). The Reynolds decomposition is applied when post-processing the raw PIV-images, while the spatial decomposition is applied a posteriori on the processed PIV images. POD is an algorithm which determines and hierarchically ranks the dominant structures in the flow with respect to their energy content, allowing the statistical capture of flow structures despite eventual shortcomings such as insufficient temporal resolution and/or sample size. The POD modes stem from calculation of the singular eigenvalue decomposition

\[
K_{ij} = \lambda_{ij}
\]

of the auto covariance matrix \( K \), given by

\[
K = U^T U.
\]

\( i \) is the total number of eigenvalues, \( U \) is a matrix where the columns consist of the instantaneous fluctuating velocity snapshots, according to

\[
U = \begin{bmatrix}
\bar{u}'_1 & \bar{u}'_2 & \cdots & \bar{u}'_{N_t}
\end{bmatrix},
\]

where \( \bar{u}'_j = u_j - \bar{u} \) for \( j = \{1, 2, \ldots, N_t\} \). \( N_t \) is the number of snapshots, 712 in the current case. The modes are then calculated and normalized by

\[
\phi_j = \frac{\sum_{i=1}^{N_t} \sqrt{\mu_{ij}}}{\sum_{i=1}^{N_t} \sqrt{\mu_{ii}}}
\]
The method stems from [31] and a more recent introduction to POD can be found in [32].

3. Results and Discussion

The middle plane is placed at z = 125 mm, and is represented by a diamond symbol in the figures. The upper plane was placed at z = 165 mm and will be represented by an x symbol in the figures. To avoid cluttering only a portion of the data have been plotted, typically every fourth point. This does not affect the results and is solely for the purpose of making the data easier to distinguish. The velocity components of the flow \((u, v)\) are denoted as the vector \(\vec{u}\). To evaluate the flow the \(u\)- and \(v\)-components of the velocity were averaged over time for one measurement (see Sec. 2.) to produce the temporally averaged velocity components \(\vec{u}\). Some of the results are then spatially averaged in the streamwise direction, denoted by \(\langle \vec{u} \rangle\). In the first section below, temporally averaged and Quadrant analysis of the velocity to discern the spatial heterogeneity of the flow are presented. In the second section, integral length scales applied to the temporally averaged velocity are discussed and in the third section POD is applied on the instantaneous velocity field. The instantaneous contribution to the Reynolds stresses are calculated according to

\[
\overline{uv} = \frac{1}{T} \sum_{i=1}^{N} S(u_i - \overline{u})(v_i - \overline{v}),
\]

where \(S\) is a sorting term. If \(\overline{uv}\) falls into quadrant \(Q\) then \(S = 1\), otherwise \(S = 0\). \(T\) is the total measuring time for each sample. An introduction to Quadrant analysis can be found in [33] or [11].

3.1. Average Velocity and Quadrant Analysis

Figure 3 shows the \(u\)-component of the time averaged velocity field of the middle measurement plane. The flow field above the rough surface exhibits a highly localized behavior induced by roughness elements, exemplified by the zone of high velocity formed at the crest of the roughness element (the ridge) positioned at \(x \approx 7.06\) m.

The average bulk velocity in the channel is \(U_b = 1.562\) m/s. A zone of negative velocity (recirculation zone) is present behind the crest of the ridge, an effect similarly visualized by [18]. Consistent with the previously mentioned study, the negative horizontal flow in the separation zone is about \(-0.15U_b\).

The asymmetric channel flow case (one rough wall opposite of a smooth one) has been well documented by [34]. Traditionally, the rough surface acts as a sink for momentum for the flow, due to the outer similarity treatment the velocity close to the surface can then be approximated using the logarithmic law of the wall. Accordingly, the maximum of the double averaged streamwise velocity component is shifted away from the rough surface [35].

For the current case, the maximum velocity \(\overline{u_{max}} = 1.45U_b\) is shifted towards the rough surface (\(y/k_r \approx 4.1\)) (see Figure 5), similar to the results of [24].
Localized roughness aberrations produce flow alterations of significant magnitude, which becomes representative for the flow close to the rough surface when applying spatial averaging. Similar local velocity alterations, for flow over a gravel bed, were reported by [19]. From Figure 5, a note can also be dedicated to the spatial heterogeneity of the flow. The measured planes are positioned with a lateral distance of only 40 mm between them yet the position of the maximum velocity differs substantially, as the maximum of the double averaged velocity is positioned closer to the center of the channel for the upper plane ($y/k_c \approx 7$). The size of the roughness elements differs no more than 3% between the planes but the standard deviation of the roughness elements is significantly higher in the upper plane. Quadrant analysis is a method to disclose the instantaneous point-contribution of the velocity fluctuations to the Reynolds stress in relation to a defined quantity $H$, defined as

$$H = \frac{u'v'}{\bar{u}'^2}$$

(8)

In short, the contribution to the Reynolds stresses is divided into one of four possible quadrants depending on the sign of the instantaneous velocity fluctuations. As $H$ increases, low magnitudes of the instantaneous velocity products are sorted out, thus only the significant contributions are left for comparison. Quadrant 2 events generally, but not always, represent ejection and similarly, quadrant 4 events represent sweeps [11]. Figure 6 present the quadrant analysis applied in at the points presented in Figure 4. Point a) is placed at $x_{\text{max}}$ showing an overwhelming dominance of Q2 events for all $H$, consistent with [18], indicating ejections of low velocity fluid away from the rough surface. Point b) and c) are placed relatively close to each other, both on either side of the shear layer separating the accelerating and recirculating flow. Both points show the highest measured $\bar{u}'v'$ magnitudes of all points, 8.41 and 7.67 m²/s² respectively. Point b) show a similar magnitude for Q2 and Q4 for $H = 0$, however, the most

![Figure 4](image_url)

**Figure 4.** The left figure (a) denote the $u'$-component of the flow field from the middle measuring plane, the colour scale represents velocity and is given in m/s, the cyan box denotes the subset in which the POD was performed. The right figure (b) clarify the points in which the quadrant analysis was performed.
dominant event for $H > 2$ is Q1. Point c), which is placed in the separation zone, show an overall dominance of Q4 events for all H. This is an indicator of sweeps of high velocity fluid moving towards the wall. Points c) and e) are placed at similar heights leeward of the roughness element, thus, displaying similar behavior. The main difference being the displayed $\overline{uv}$ magnitudes which have dissipated significantly by point e). Presumably, if no other roughness element would occur downstream, Q2 events would again become dominant as similarly theorized by [18]. However, within the selected section there is no visible zone of reattachment. Surprisingly, for $H < 3$, the major contribution in point d) is Q3 followed by Q1. d) also has the lowest recorded measured $\overline{uv}$ magnitude for $H = 0$, which is $-0.0747 \text{ m}^2/\text{s}^2$. For larger $H$ Q2 events become dominant. One possible reason for this might be traces of decelerating high velocity flow from the ridge still present where the point is located.

3.2. Spatial Velocity Correlation

To characterize the size of the flow structures above the rough surface a correlation length approach is utilized. The streamwise spatial velocity correlation is calculated by [36]

$$\overline{\rho} = \frac{1}{\pi} \int_{x_1}^{x_2} \overline{\rho(x,y)\rho(x+r,y)} \, dx$$

where $\rho = (u, v)$, $r$ is the streamwise incremental coordinate and

$$\overline{\rho} = \rho(x,y) - \frac{1}{x_2-x_1} \int_{x_1}^{x_2} \rho(x,y) \, dx = \rho - \langle \rho \rangle.$$  

Using Equation (2), a characteristic length scale can be derived for each velocity component. This operation continues from the crest (not $y/k_z = 0$) to $y/k_z \approx 8$, and an integral length scale is calculated for each acquired auto-correlation function, see Figure 7. The values labeled smooth are measurements near the Plexiglas wall opposite of the rough surface in the center plane.

Figure 5. The double averaged $u$-component of the velocity for both measured planes, $U_0$ is the average free stream velocity. The red line denotes the height of the ridge, below the line the available amount of spatial samples decline.
Figure 6. Instantaneous $\mathbf{HV}$ contributions from the four quadrants (Q1-4) at the points (a)-(e) visible in Figure 4(b). The sub-figures share a common x-axis and the y-axis is given by Equation (7).
and are meant to represent a smooth wall case. These values are similar for both the upper and middle case, therefore only one the middle one is displayed.

Near the surface, the flow exhibit very different behavior between the two planes up until about half the channel \((y/k_c \approx 8)\). The middle plane show a sharp increase in the length scale at \(y/k_c \approx 2.7\), about \(0.37k_r\) above the crest of the roughness element with a magnitude of \(\tau/\tau_r \approx 1.6\). The peak, to a degree, indicates the shear layer forming between the bulk and recirculation zone following the roughness peak visible in Figure 4. Scaling the results with the integral length scale of the rough surface, \(\tau_r\), as done in Figure 7 provides some interesting insight into the size of the flow structures. There is a strong correlation between the length scales of the rough surface and the flow above the rough surface since \(\tau/\tau_r \approx 1\) in the bulk flow, see Figure 7. The obvious explanation for this would be that the rough surface creates similar length scales of the flow above the rough surface. Which would also suggest that the effects of the surface roughness is visible in the entire channel and not just in the vicinity of the wall, a notion proven for similar flow applications \[19\] \[37\]. This is a likely hypothesis and the idea is quite intriguing, however, the extent of this phenomenon has to be further investigated before any definite conclusions can be drawn.

3.3. Proper Orthogonal Decomposition

While the integral length scale was applied to the mean velocity, POD was applied to the instantaneous velocity fluctuations. The subsets from the middle plane could not be measured at the same time, hence, any perturbations in the flow cannot be tracked from one subset to another and thereby limiting the visualization of the data. Additionally, the temporal resolution made it difficult to capture sufficient snapshots of the same structure. However, POD is a statistical tool which provides an opportunity to visualize the distribution of energy within each subset, thereby avoiding the problem of synchronized pictures and large temporal resolution. As mentioned in Sec. 3.1, the effects on the mean velocity and higher-order statistics suggest vortex shedding behind the ridge in the
The first three modes from the POD, the left figure is the first mode, the textboxes denote the amount of captured kinetic energy within the mode. The location of the POD is given by the cyan box in Figure 4. To further investigate this, POD was applied to a subset downstream of the roughness element positioned close to the center of the middle field as defined by the cyan box in Figure 4. In Figure 8 the first three modes of the POD are visualized. These three modes capture in total 33.2% of the fluctuating velocity kinetic energy associated with the modes. The modes are dimensionless and the energy content comes from the eigenvalues in Equation (3). Assuming that the POD-mode ends at 20% of the maximum, a longitudinal length scale of about $1.55 \lambda_{ POD}$ can be determined, which is similar to the peak in Figure 7. It should be noted that POD-modes cannot be automatically assumed to represent vortices. Nonetheless, it can be applied to zones where shedding is known to appear and identify the dominant structures of the flow, as in this case.

The scale in Figure 8 is between −1 and 1, where 1 corresponds to the maximum energy captured within the mode. The first mode represents the flow structures containing the most energy, which also represents the flow structures rendering the peak in the integral length scale (Figure 7).

4. Conclusion

Results from PIV measurements of flow over a rough hydraulic surface are presented. The surface is produced from laser scanning an existing rock surface and the dimensions of the experimental tunnel are made to reflect real conditions for hydropower tunnels. A likely treatment of such surfaces in the industry is to assume uniform (and thereby small scale) roughness which, according to these results, would lead to erroneous estimations of flow parameters. The results include profiles of double averaged velocity, higher-order statistics, quadrant analysis, correlation length scales and POD. The presented measurements reveal a highly localized behavior of the flow connected to the rough surface. Even small deviations from the local mean height in the surface roughness produce perturbations in the flow which will be visible in the results. In contrast to classical results in asymmetric channel flow the maximum velocity is shifted towards the surface. This shows that the effects from the rough surface are large enough.
to manifest even in the double averaged velocity. It should be noted that the roughness element studied is not unique, but similar ones occur regularly on the rough surface. Therefore, using large spatial samples would produce the same distortions when averaging. The higher order statistics indicate that the flow above and behind the ridge is characterized by ejection and intermittent bursts of velocity, this is also where the highest point-contributions to the Reynolds stresses where recorded. Similarly, earlier measurements showed higher frequencies of fluctuating pressure at the same ridge. Research has shown that these are unfavorable conditions for rock surfaces from a durability point of view and may hasten or induce an eventual process of tunnel breakdown. As theorized, the problem of tunnel breakdown is likely connected to the flow-roughness effects. Evaluation of the correlation lengths of the flow reveals a significant difference between how the roughness elements interact with the flow. Both the integral length scales and POD approximately predicted the position of the largest flow structures formed in vicinity of the rough surface at $y/k_r \approx 3$. Consequently, similar data can be obtained from both the time-averaged velocity and the instantaneous velocity fluctuations. The streamwise length scales of the flow holds close resemblance to the length scales of the rough surface, since $\tau/\tau_r \approx 1$ for $y/k_r > 7$. In contrast to Townsends’s similarity hypothesis where the effects of the rough surface is visible beyond the range of the rough surface, and throughout the channel. Similar effects have been shown in studies concerning flow over riverbeds, dunes or in rivers. It should be noted that such cases usually employ lower Re and larger roughness height to surface ratio and would not regularly be associated with the current application. It does, however, highlight that for hydropower applications, rough surfaces cannot be treated as uniform and only friction-inducing. This is particularly important when modelling flow using CFD, whose role has grown vastly in many industrial applications the past two decades. The results provided here show that the resolution of the roughness is very important, which could have large implications on the future evaluation of hydropower tunnels. A different proposed approach would involve a modification of the uniform wall functions currently used by today’s standards. A thorough mapping of the turbulent kinetic energy in correlation with the rough surface would yield the necessary data, as shown by the quadrant analysis in this study. Thereby the law of the wall could be modified with a spatially stochastic localized increase in wall-near velocity gradients. The roughness length-scales employed in this study might suffice for such an endeavoring as implied by the integral length-scales, however, different methods of deriving these should nevertheless be explored. One limitation of this study is the usage of only one rough wall. Hence, the flow in an actual hydropower tunnel cannot be claimed to be fully understood yet, albeit further understood. There has been no indication of eventual scaling effects between the experiments and the actual case. But if one would consider the problems within hydropower tunnels today and the agreement with other studies the authors assume that the scaling effects, if any, would be insignificant.
Acknowledgements

The research presented was carried out as a part of “Swedish Hydropower Centre-SVC”. SVC has been established by the Swedish Energy Agency, Energiforsk and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University.

References


L. R. Andersson et al.


Localized roughness Effects in non-uniform hydraulic waterways

Authors:

Article submitted to:
Journal of Hydraulic Research
Hydropower tunnels are generally subject to a degree of rock falls. Studies explaining this are scarce and the current industrial standards offer little insight. To simulate tunnel conditions, high Reynolds number flow inside a channel with a rectangular cross-section is investigated using Particle Image Velocimetry and pressure measurements. For validation, the flow is modelled using LES and a RANS approach with $k-\varepsilon$ turbulence model. One wall of the channel has been replaced with a rough surface captured using laser scanning. The results indicate flow-roughness effects deviating from the standard non-asymmetric channel flow and hence, can not be properly predicted using spatially averaged relations. These effects manifest as localized bursts of velocity connected to individual roughness elements. The bursts are large enough to affect both temporally and spatially averaged quantities. Both turbulence models show satisfactory agreement for the overall flow behaviour, where LES also provided information for in-depth analysis.

Keywords: Hydropower, CFD, Validation, Hydraulic Roughness, PIV

1 Introduction

The hydropower industry in Sweden experienced significant growth in the period of 1950 to 1990 and a vast system of water conveying tunnels where excavated as a result. It is not an uncommon problem for hydropower tunnels to collapse (Bratveit et al., 2016; Reinius, 1986), and it has been theorized that pressure fluctuations in connection with specific roughness elements often cause these failures. In accordance, a study by Patel et al. (2017) showed that oscillating injection of fluid into rock caused larger damage and at lower pressures than under constant pressure. While the aforementioned study is interesting, the actual dynamics within hydropower tunnels are largely unknown, making comparison difficult. Modelling the flow inside such tunnels is problematic, as there is no clear way to distinguish between rough surface flows in the classical sense and flow past obstacles. Yet, to be able to distinguish between the two cases has proven to be important (Andersson et al., 2012). Using fix, uniform and small-scale roughness simplifies analysis of the flow, numerous studies have focused on roughness in the form of e.g. wall-mounted ribs (Leonardi et al., 2003), wavy walls (Kruse et al., 2006; Nakagawa and Hanratty, 2001, 2003) and pyramids (Sedighi et al., 2015). This assumption is however in contrast with conditions in the hydropower industry where the roughness characteristics of tunnels commonly are similar to random terrain.
In addition, the scales of roughness in unlined hydropower tunnels range from a few millimetres to meters, which may be in the range of $\approx 10\% - 20\%$ of the hydraulic radius. The same can undoubtedly be said about other technical applications such as flow over river beds (Bennet and Best, 1995; Buffin-Bélanger et al., 2006).

Numerous studies within the fluid dynamics field have been devoted to the understanding of rough surface flows, and the applications of the research have proven to be important in technical applications. Two reviews by Jimenez (1999, 2004) provide a good overview of both smooth and rough wall flows. One common way to handle surface roughness is to assume a uniform sand grain roughness factor (typically denoted $k_s$) for the rough surface, rendering a spatially averaged resistance when evaluating the flow. This can either be defined by characteristics of the surface roughness or $\Delta U^+$ (Lauder and Spalding, 1974), which is an offset constant accounting for the shift in velocity distribution due to the roughness. The latter definition provides a common and widely used method of describing the extent of the roughness sublayer. However, $\Delta U^+$ depends solely on the velocity distribution within the boundary layer and is difficult to predict for a given roughness a priori (Schultz and Flack, 2005). In many applications accurate velocity measurements in situ are rarely possible and experimental results on natural surfaces of large-scale roughness are scarce, this problem was highlighted by Grass (1971) but to a degree still remains today. Hydraulic roughness in civil-engineering applications are often estimated from features of the roughness and expressed in terms of Manning- or Chezy coefficients or by characteristic grain diameters (Chanson, 2004). These approaches have a long track record but only provide spatially averaged quantities and nothing about the actual dynamics within the tunnel.

To investigate the effect of the large-scale roughness in a tunnel, the topography of an existing blasted rock-tunnel was captured by using high-resolution laser scanning, a method proven to be effective for establishing surface roughness (Bråteit et al., 2012). A ten meter long computer model was created from a 1:10 scale sidewall of the laser-scanned surface. Additionally, the same geometry was 3D-printed to a physical model used in experiments by Andersson et al. (2015, 2016). Earlier measurements show a very localised behaviour of the flow above the rough surface, similar to Bennet and Best (1995). The scope of this article will be: (i) To visualize the flow dynamics connected to tunnel roughness at high Reynolds number in order to assess the current industrial evaluation standards of e.g. numerical wall functions or uniform roughness treatment. (ii) To evaluate how to properly model the flow inside the tunnels both correctly and in a way that is feasible for the industry. (iii) To accurately determine the wall shear using head-loss measurements and a channel-decomposition method. (iv) To connect the findings to other further documented fluvial flows. Two types of simulations are applied to validate the experimental results. The first simulation is the RANS based $k-\varepsilon$ model. In the second, an LES-model has been performed. The LES was restricted to a smaller domain of the 10 m channel, with the initial data provided from the $k-\varepsilon$ model. In addition to temporal averaging, adding a spatial averaging to a plane parallel to the mean flow may allow for a uniform representation of the local flow variations. This technique is called double averaging (Nikora et al., 2007) and is used in some of the reported results.

2 Numerical and experimental setup

2.1 Rough surface model

The rough surface model used in both the experiments and the simulations was a side wall of an existing rock tunnel whose topography was captured by high-resolution laser scanning ($\approx 200$ points/m$^2$). One of the main characteristics used to describe a rough surface is the height distribution function $p(h)$, which was proven to be Gaussian. Height (denoted $h$) is defined as any local elevation measured with respect to the average surface elevation, which is set to zero. The meaning of $p(h)$ is that the frequency of any surface height between $h$ and $h + dh$ is $p(h)dk$ (Zhao et al., 2007e).
Another important factor for characterizing a rough surface is the Root Mean Square (RMS) roughness factor, which denotes the average height of the roughness elements on the surface. Since the mean elevation is set to 0 the RMS is equal to the standard deviation. For practical reasons, measuring head loss or boundary layer shearing ($\Delta U^+$) to determine the corresponding sand grain roughness factor is not a realistic option. Therefore the RMS roughness factor is calculated solely from the physical height of the surface, defined as (Bråtveit et al., 2012; Sarkar and Dey, 2010)

$$h_s^2 = \int_{-\infty}^{+\infty} h^2 p(h) dh.$$  

(1)

It should be noted that $h_s$ does not take into consideration e.g. shape or aspect ratio of the roughness. Using Eq. 1, $h_s$ is determined to 9.4 mm. $y = 0$ is set to be the average elevation of the rough surface. $z = 0$ emanates from the right wall relative to the flow direction and $x = 0$ originates from the channel inlet and points towards the channel outlet.

2.2 Experimental setup

The experimental setup consisted of a channel, two tanks placed up and downstream of the channel respectively, pressure gauges, a pump, an electromagnetic flow meter and a Particle image velocimetry (PIV) system. One of the walls in the channel was replaced with the rough surface previously described in Sec. 2.1. The channel is 10 m long with a width, $b$, of 0.25 m. The average distance between the rough surface and opposing wall, $d_r$, is 0.145 m. The upstream tank is filled with water and provided an even head on the system in addition to preventing air entrainment inside the channel. The downstream tank collected the water from the channel which was funnelled back to the upstream tank via the pump. The flow rate was set to 64 l/s. Differential pressure gauges were flush mounted along the walls of the channel, measuring the head loss every 2 m. A rough schematic of the experimental setup can be found in Fig. 1 and a more thorough explanation of the experimental setup can be found in the freely available article by Andersson et al. (2016).

![Figure 1](image-url) A schematic of the experimental setup used in the campaign. Please note that the figure is not to scale and that the channel has been mirrored to provide a more comprehensible view regarding the setup.

A section of the channel, indicated by the red box in Fig. 1, starting at 6 m and ending at 8 m downstream of the channel entrance is denoted as the measuring section, since the pressure and PIV measurements where performed here. Within that section, one plane ($x$-$y$) starting at $x = 6.8$ m has been used as the validation case between the experiments and simulations, see Fig. 2. The plane is positioned at $z = 0.125$ m, corresponding to the middle of the channel and is henceforth denoted as "middle". At approximately 7.06 m downstream, a roughness element with the shape of a ridge can be found (see Fig. 2), this element will be referred to as the ridge. A flush mounted pressure sensor was positioned at the ridge represented by the cyan circle in Fig. 2, about 5 cm...
Figure 2 The rough surface in the measuring section, the cyan line marks the position of the plane captured by the PIV and the cyan circle marks the position of the pressure sensor. The colour of the surface represents the relative gradient \( \frac{\partial h}{\partial x} \) of the surface topography beside the plane to prevent the sensor of immediately interfering with the PIV-measurements. The maximum height of the ridge in the middle plane is 9.44 mm, which is very close to \( h_s \). One can therefore conclude that the ridge is a fitting representation of the roughness of the entire surface. The ridge in question is far from unique on the surface as similar ones appear at regular intervals, therefore, the sample size is deemed large enough to be spatially independent.

2.3 PIV-setup and error estimation

The PIV-system used was a commercially available system from LaVision GmbH. It consisted of a Litron Nano L PIV laser, i.e. a double-pulsed Nd:YAG with a maximum repetition rate of 100 Hz and a pulse energy of 50 mJ. For image acquisition, a 10-bit LaVision FlowMaster Imager Pro CCD-camera with a spatial resolution of 1280 x 1024 pixels per frame, fitted with a Nikon 50 mm f/1.8D lens, was used. Sheet optics and mirrors produced a 1.5 mm thick laser sheet directed to the desired location. The laser was mounted on a traverse allowing a simultaneous repositioning of the laser sheet and camera of up to 500 mm in the \( x \), \( y \)- and \( z \)-directions. In order to prevent any large loads acting on the channel, in addition to restricting vibrations interfering with the camera, the traverse was placed and operated independently of the experimental channel. Due to limitations of the field of view of the camera and laser power, it was not feasible to capture the entire measuring plane in one frame. Thus, the plane was divided into 14 smaller subsets all measured individually and manually merged together. The spatial dimensions of each subset where about 100 mm (\( x \)-direction) by 80 mm (\( y \)-direction). To consider the laser sheet attenuation in the image periphery, subsequent positions where set to give a 30 mm overlap of the images. The tracer particles used were the previously proven feasible (Andersson et al., 2012) AkzoNobel’s Expancel 461 WU 20 hollow thermoplastic spheres with a diameter ranging from 2-30 \( \mu \text{m} \), and a density of 1.2 g/cm\(^3\).

The measurements were performed with a frequency of 75 Hz during 9.49 s, corresponding to a total of 712 image pairs for each recorded set. To ensure a sufficient temporal sample size both the time-averaged velocity and turbulent kinetic energy was examined after each recorded set. At approximately 490 samples the temporally averaged velocity converges towards a stable value and beyond 560 samples the velocity differs no more than 1.5% from the converged value. To account for the localized variations in velocity and pixel displacement, the time interval between the laser pulses ranged from 150 \( \mu \text{s} \) - 275 \( \mu \text{s} \) depending on the measuring position. The typical mean pixel displacement over the whole velocity field where 0.3 pixels in the \( y \)-direction and 7 pixels in the \( x \)-direction with a characteristic particle image diameter of 2 pixels.

The overall measuring accuracy in PIV is a product of several features ranging from the recording process to the methods of evaluation (Raffel et al., 2013). A cornerstone of all experimental design is proper randomization of the measuring procedure. Accordingly, the effects of extraneous factors that may be present will have less impact on the results (Montgomery; 2009). The measure-
ment uncertainties consist of those due to systematic biased errors and random precision errors (or due to erroneous measurements) (Coleman and Steele, 1999). The biased error associated with the scaling from pixels to meters is estimated to be 0.5%, this was derived from measuring over a known length-scale. The primary source of random error is introduced by the sub-pixel estimator in the cross-correlation an error estimated to be 10% of the particle image diameter [pixels] as seen through the camera (Balakumar et al., 2009). Therefore the estimated random error of the measured velocity vector in each interrogation area is about 4% for the streamwise velocity component.

Stitching together the domain using the measured sets may create discontinuities in the borders between the subsets. However by careful stitching, a good statistical convergence and choosing appropriate overlap the largest discrepancy between two sets was no more than 1.3% in the streamwise direction. In the spanwise direction, the discrepancy is less than 1%. The rough surface reflected light from the laser which in some images saturated the camera, inhibiting measurements of the near-wall flow. These effects where highly localized, generally within 0 ≤ y/h_s < 1 of the rough surface and therefore never affected the bulk-flow. Since the rough surface was placed on a side wall of the channel, the camera was placed above the channel facing downward, see Fig. 1. Roughness elements closer to the camera occasionally covered parts of the plane intended for measuring, generating additional difficulties in measuring the near wall behaviour of the flow.

Discretization and simulation setup

For initialization, a RANS simulation with k − ϵ turbulence model was implemented on the entire domain. The inlet boundary condition was set to a flow rate of 64 l/s (same as in the experiments), which results in a Reynolds number $Re = (d_r/2)U_0/\nu \approx 200 000$ where h is the channel height, $U_0$ is the bulk velocity and $\nu$ is the viscosity. The Roughness Reynolds number $h_s^+ = h_s U_\tau/\nu \approx 1300$ (Schlichting and Gersten, 2003), meaning that the flow can be considered fully rough and fully turbulent in both the experiments and simulations. The domain was discretized into smaller subgrid domains using the commercial software ICEM CFD v.15. The walls of the domain had a tetra mesh size of 5 mm while the elements close to the rough surface was refined to 2 mm, rendering a mesh size of approximately 25000k elements and 5000k nodes. The mesh size was chosen from an earlier case by Andersson (2013), where a grid convergence study was performed on a similar flow case (same surface but shorter channel). Two cases of slightly fewer and higher number of elements were tested to confirm mesh independence. For the LES, the 10 m domain was reduced to a 1 m section spanning the region of interest using the RANS results as an initial and inlet condition. Similarly, the reduced domain was discretized into smaller subgrid domains where the walls of the domain had a tetra mesh size of 5 mm while the elements closest to the rough surface have been refined to a size of 1 mm. This resulted in an average $y^+ = 33$, a mesh of 1200k nodes and 5700k elements. A quantitative way of assessing the quality of the mesh is to examine the percentage of kinetic energy resolved by the mesh (Davidsson, 2009). The analysis show that on average, ≈ 80% of the kinetic energy is resolved, which is deemed sufficient (Pope, 2001). The outlet boundary condition average static pressure was set to 0 Pa. To solve the LES equations the commercial software ANSYS-CFX v.15 was used with a Smagorinsky model for closure. The transient simulations ran for a total of 10 s with a timestep of 0.00025 s, resulting in an RMS Courant number of 3.22 (maximum 32.18). To match the PIV, every 50th timestep was captured for the results. A convergence criterion of $10^{-5}$ was used for the RMS residuals for the mass and momentum.

3 Results and discussion

The evaluated plane is placed 6.78 m downstream (x-direction) of the tunnel entrance having the length 0.48 m. To avoid cluttering only a portion of the data (≈ 20%) will be included in the
presented figures, this does not affect the analysis and the sole purpose is to make the presented data easier to distinguish. The velocity components of the flow \((u, v)\) are denoted as the vector \(\mathbf{u}\). To evaluate the flow the \(u\)- and \(v\)-components of the velocity were averaged over time for one measurement to produce the temporally averaged velocity vector \(\bar{\mathbf{u}}\), some of the results are then spatially averaged in the streamwise direction, denoted by \(\langle \bar{\mathbf{u}} \rangle\) (Nikora et al., 2007). This produces a one-dimensional profile representing the flow over the rough surface. In the first section, the velocity, both averaged and double averaged, are evaluated. In the following section, the friction velocity will be evaluated using an approximative method based on the head loss. Both mentioned sections from this article include data from PIV, LES and the RANS model. The following two sections investigate the vortex shedding using higher order moments, pressure measurements and Fourier transforms. However, in these sections the data will only include PIV and LES as RANS does not produce any reliable instantaneous data.

3.1 Velocity field

The complete set of pressure measurements by Andersson et al. (2016) showed that although the pressure varied over the rough surface, the absolute largest oscillations occur at the roughness peak presented in this article, see the cyan circle in Fig. 2. Similarly, the velocity exhibits a highly localised behaviour connected to the roughness elements of the surface, see Fig. 3. One manifestation of this phenomena is the zone of high velocity formed at the crest of the ridge, positioned at \(x \approx 7.06 \text{ m}\). The average bulk velocity \(U_0\) is 1.761 \text{ m/s} for the PIV and 1.836 \text{ m/s} respectively.

![Figure 3 Velocity field of the streamwise component \(\bar{u}\) for the middle plane of the PIV (left) and LES (right). The slight difference in the bottom profiles is due to small localized masking errors while evaluating the PIV](image)

Immediately downstream of the ridge, a zone of negative velocity can be seen in the flow field, an effect similarly visualized by Bennet and Best (1995). Similar to the previously mentioned study, the negative horizontal flow in the separation zone is about \(-0.130U_0\) for the PIV and \(-0.133U_0\) for the LES respectively, indicating severe shear drag in the separation zone. The average horizontal velocity is -0.0434 \text{ m/s}. In Fig. 4 the double averaged velocity profiles from the PIV, LES and RANS can be seen. The asymmetric channel flow case (one rough wall opposite of a smooth one) has been well documented by Hanjalic and Launder (1972). Traditionally, the rough surface acts as a sink for momentum for the flow, and due to the outer similarity treatment the velocity close to the surface can then be approximated using the logarithmic law of the wall. Accordingly, the maximum of the double averaged streamwise velocity component is shifted away from the rough surface (Nakagawa et al., 2005).

From Fig. 4 it is clear that the expected shift in the velocity profile, visualized by Hanjalic and Launder (1972), is absent. Instead, the maximum of the double-averaged (DA) velocity is shifted towards the rough surface \((y/h_s \approx 4.1)\). The ridge produces local flow alterations of significant magnitude, which becomes representative for the flow close to the rough surface when applying
spatial averaging. Consequently, neither assuming uniform roughness nor the outer-layer similarity treatment may prove satisfactory. Similar local velocity alterations for flow over a gravel bed was reported by Buffin-Bélanger et al. (2006). Again, it should be noted that the roughness elements captured in these frames are not unique for this surface but can be considered average. Therefore, choosing a larger sample plane for the spatial averaging would still produce the same shift in the double averaged velocity profiles. Both turbulence models manage to adequately capture this phenomenon, specifically the spanwise position of the maximum DA velocity.

3.2 Estimation of $u_\tau$

The wall shear stress on the rough wall $\tau_r$ can be evaluated by (Chanson, 2004)

$$\tau_r = \rho g R_r S_f,$$  \hspace{1cm} (2)

where $S_f$ is the gradient of the friction line defined as $-\frac{1}{\rho g} \frac{dp}{dH}$, $R_r$ is the hydraulic radius with regard to the rough wall and $\rho$ is the fluid density. $\frac{dp}{dH}$ is derived from the head loss measurements (Andersson et al., 2016). In river engineering it is common practice to decompose the wetted perimeter, $P$, and the cross sectional area, $A$, into parts when properties (such as roughness) vary signiﬁcantly over the considered cross section. A good review of this practice is given by Yen (2002) and one of the simpler methods dates back to Einstein (1942). The rectangular cross section of the channel is decomposed into a rough and a smooth part and after some rearrangements, using this methodology the hydraulic radius can be expressed as

$$R_r = \frac{A}{P} = d_r - \left(2 \frac{d_r}{b} + 1 \right) \left( \frac{n_s U_0}{\sqrt{S_f}} \right)^\frac{1}{2}.$$  \hspace{1cm} (3)

The Manning equation has been used in the derivation of Eq. 3, it should be emphasized again that the flow is considered fully rough, which is a requirement for using the Manning equation. $n_s = 0.010$ $s/m^{1/3}$ represents the Manning’s number for the smooth walls (i.e. glass or plastic) of the channel (Chanson, 2004). Besides the assumption of the decomposition of $P$ and $A$, Eq. 3 also assumes that the pressure gradient, $S_f$, is constant for all decomposed parts. $U_0$ is the bulk flow velocity for the measurement section. Using Eq. 2 in $u_\tau = \sqrt{\tau_r / \rho}$, the friction velocity can be evaluated, see Tab. 1. This method of decomposition should be considered an approximate way of estimating the friction velocity, but it still reﬂects more representative conditions than just considering average values for the entire cross section (smooth and rough surfaces considered jointly). Table 1 show good agreement between LES and PIV, the estimation of $u_\tau$ differ 1.5%.
Table 1 Results from applying Eqs. (2)-(3) on the experimental and simulated data

<table>
<thead>
<tr>
<th>Data set</th>
<th>$U_0$ [m/s]</th>
<th>$S_f$ [-]</th>
<th>$R_c$ [m]</th>
<th>$\tau_r$ [N/m$^2$]</th>
<th>$u_r$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiments</td>
<td>1.761</td>
<td>0.0547</td>
<td>0.096</td>
<td>51.6</td>
<td>0.227</td>
</tr>
<tr>
<td>LES</td>
<td>1.836</td>
<td>0.0541</td>
<td>0.093</td>
<td>49.3</td>
<td>0.222</td>
</tr>
<tr>
<td>$RANS(k-\epsilon)$</td>
<td>1.830</td>
<td>0.0372</td>
<td>0.078</td>
<td>28.4</td>
<td>0.169</td>
</tr>
</tbody>
</table>

The agreement with RANS is from this aspect quite poor compared to the LES due to the under-prediction of the head loss.

3.3 Higher-order statistics

Similar to quadrant analysis, higher-order statistics can be used to determine a variable’s spread around the mean in addition to the skewness of its temporal distribution. In this section, the third and fourth order moments, skewness and flatness respectively, are applied to the PIV and LES, see Fig. 5. None of these statistics shows anything of use in the bulk-flow since they are arbitrarily close to zero, therefore, the spatial averaging of the moments will be limited to the area around the selected roughness element (the ridge) in the presented figures.

![Figure 5: Flatness $F$ (Left) and Skewness $S$ (Right) of the $u$ and $v$-component of the velocity](image)

The trends of the skewness of the velocity agree between the LES and the PIV, except from the magnitude of the $u$-component at $y/h_s \approx 4$. At $y/h_s \approx 4$ the skewness of the $u$ and $v$-components are evenly distributed around zero, the $v$-component being positive and $u$ negative. Hence, second quadrant events are dominant in this area, associated with strong turbulent production, ejection of fluid away from the wall and rapid oscillations in the flow (Kim et al., 1987). Similar to Andersson et al. (2018); Bennet and Best (1995), where quadrant analysis at $\langle \bar{u} \rangle_{\text{max}}$ showed an overwhelming dominance of Q2 events. The peaks in the flatness are caused by surges in both velocity components, connected to the vortex shedding occurring at the roughness element. This is also according to Bennet and Best (1995).

3.4 Vortex shedding

It is clear that the local perturbations from the surface roughness are enough to produce non-expected irregularities in the time-averaged quantities. The temporally averaged velocity show recirculation at the same position. These results, along with results presented by Andersson et al. (2018) suggest vortex shedding occurring at the roughness element. When the flow is accelerated over the roughness element, the pressure will decline accordingly and fluid will congregate in the
low-pressure zone downstream of the roughness element. This effect precipitates the growing of the wake until ejection occurs. To evaluate the frequency of the shedding a Fourier transform is applied to the velocity at one specific point close to the crest of the roughness element, marked by the cyan circle in Fig. 2. The velocity is sampled in the wake just downstream of the crest of the roughness element.

Figure 6 Fourier transform of the velocity, the upper is PIV and the lower is LES

Figure 6 depicts the frequency spectrum of the velocity from both the LES and the PIV. Both show a peak around 9.54 and 9.46 Hz, corresponding to a Strouhal number of \( St = \frac{fh_s}{U_0} = 0.055 \) and 0.057 respectively for the LES and PIV, where \( f \) is the frequency. In spite of larger \( Re \) and the difference in roughness shape, the recorded frequencies are of a similar order to those presented by Acarlar and Smith (1987). For comparison, the Fourier transform was also applied to the pressure data sampled at the crest of the roughness element. Although not completely in-line with the measured PIV-sets (however, the same roughness element) the pressure sensor is placed with an off-set of about 2 cm perpendicular to the PIV plane to prevent the sensor from modifying the shape of the roughness element. The pressure was sampled at 200 Hz at around 45 minutes, hence, a considerably larger amount of samples exist for the pressure compared to the velocity, see Fig. 7.

Figure 7 Fourier transform of the pressure measurements

The large peak in the pressure data spans several Hz, which encompass both peaks captured from the LES and PIV. This indicates that the LES manages to capture the shedding induced at the roughness elements. Additionally, it is an indicator that pressure measurements can be a helpful and reliable complement to PIV measurements. This can be advantageous, since pressure measurements are relatively cheap and easy to perform compared to the other methods of visualisation used in
this study, and the data is quite effortless to handle.

4 Conclusions

Results from a validation case have been presented, where the flow inside a channel has been investigated using PIV, pressure measurements and CFD. One of the walls of the channel has been replaced with a surface whose roughness is large, typically 10-20%, compared to the hydraulic radius of the tunnel. At the rough surface, a specific roughness element was chosen for investigation. This roughness element would perhaps not catch any attention during a visual inspection and is a fitting representation of the average roughness element on the surface. However, the roughness element induce unexpected dynamics in the flow. Earlier studies have shown that identification of such roughness elements are important, as these flow dynamics might be unfavourable for rock walls, which has been shown by experiments in hydraulic fracturing. By the current industrial standards, the likely treatment of rough surfaces involves calculating spatially averaged friction induced quantities derived from mean flow parameters. As has been proven in this study, specific roughness elements will refract from this behaviour and introduce perturbations in the flow large enough to manifest in both spatially and temporally averaged quantities. This can be seen in the apparent shift in the maximum streamwise velocity component, which differs from traditional asymmetric rough channel flow. The higher order moments show that the roughness element induces intermittent bursts of velocity into the flow, in combination with quadrant two events, implying ejection of fluid away from the wall. This fluid motion is often associated with a strong production of turbulence and rapid oscillations in the flow, which could be seen in the pressure measurements as well as in the applied numerical models. These localized dynamics may indeed become dominant for the flow inside the channel in its entirety since similar roughness elements occur regularly along the rough surface. The RANS approach proved to be relatively easy to set up, versatile and cheap on the computational resources, therefore the method could with advantage be used in cases such as: Identifying problematic roughness elements, since the effects where visible in the temporally averaged results. Seeking rough estimates of certain flow parameters. Anything further than that, and RANS will most likely produce dubious results, especially in proximity to the wall, where the flow is modelled using uniform functions. An example is the head loss, and thereby $u_\tau$, which was poorly predicted for RANS. LES proved better at predicting the head loss which leads to a more accurate prediction of $u_\tau$ from the head loss. Additionally, the LES model did capture the behaviour of the flow above the rough surface, such as the vortex shedding. Conclusively, LES holds many advantages compared to RANS, however, it is significantly more demanding from the computational aspect. Hence, the usage of LES in the industry today is sparse since quick results are often preferred.

Acknowledgements

The research presented was carried out as a part of "Swedish Hydropower Centre - SVC". SVC has been established by the Swedish Energy Agency, Energiforskningsinsitutet and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University. www.svc.nu.
**Notation**

\(\langle a \rangle\) = Spatial averaging of the a-variable (–)

\(\overline{a}\) = Temporal averaging of the a-variable (–)

\(\hat{a}\) = Fourier transform of the a-variable (–)

\(f\) = Fluctuating frequency (Hz)

\(k\) = Roughness height relative to the mean roughness height (m)

\(h_s\) = RMS roughness factor (m)

\(R_e\) = Reynolds number (–)

\(R_r\) = Hydraulic Radius (m)

\(S_f\) = Gradient of the friction line (–)

\(U_0\) = Average bulk flow velocity (m s\(^{-1}\))

\(u, v\) = Streamwise and transverse velocity components respectively (m s\(^{-1}\))

\(\langle uv \rangle\) = Reynolds shear stress (Pa)

\(u_\tau\) = Friction velocity (m s\(^{-1}\))

\(x, y, z\) = Spatial coordinates (m)

\(\tau_r\) = Wall shear stress (Pa)

**References**


Inlet blockage effects in a free surface channel with artificially generated rough walls

Authors:

Article published in:
7th International Symposium on Hydraulic Structures Proceedings, 2018, Open access
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L. R. Andersson
Luleå University of Technology, robin.andersson@ltu.se

A.J. Burman
Luleå University of Technology

J.G.I. Hellström Dr
Luleå University of Technology, gunnaz.hellstrom@ltu.se

P. Andreasson Prof
Vattenfall Research and Development, patrik.andreasson@vattenfall.se

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Inlet Blockage Effects in a Free Surface Channel with Artificially Generated Rough Walls

L. R. Andersson1, A. J. Burman1, J. G. I. Hellström1 & P. Andreasson1,2

1 Luleå University of Technology, Luleå, Sweden
2 Vattenfall Research and Development, Älvkarleby, Sweden

E-mail: robin.andersson@ltu.se

Abstract: When considering free surface flow in channels, it is essential to have in-depth knowledge about the inlet flow conditions and the effect of surface roughness on the overall flow field. Hence, we hereby investigate flow inside an 18m long channel by using Particle Tracking Velocimetry (PTV) and Acoustic Doppler Velocimetry (ADV). The roughness of the channel walls is generated using a diamond-square fractal algorithm and is designed to resemble the actual geometry of hydropower tunnels. Four different water levels ranging from 20 to 50 cm are investigated. For each depth, the inlet is blocked by 25 and 50% at three positions each, at the centre, to the right and to the left in the flow-direction. The flow is altered for each depth to keep the flow velocity even throughout the measurements. PTV is applied to measure the velocity of the free water surface; four cameras are placed above the setup to capture the entirety of the channel. The results show a clear correlation between roughness-height and velocity distribution at depths 20-30 cm. The surface roughness proved effective in dispersing the subsequent perturbations following the inlet blockage. At 50 cm, perturbations from the 50% blockage could be observed throughout the channel. However, at 20 cm, most perturbations had subsided by a third of the channel length. The ADV was used to capture the velocity in a total of 375 points throughout the channel, at a depth of 50 cm with no inlet perturbations.

Keywords: Hydraulic roughness, PTV, diamond-square algorithm, free-surface flows.

1. Introduction

When considering free surface flow in channels, it is essential to have in-depth knowledge about the inlet flow conditions and the effect of surface roughness on the overall flow field. Often the surface roughness is replaced by a spatially averaged friction-inducing quantity and, similar to smooth walls, parameters are subsequently derived from the mean flow. This saves computer cost and simplifies examination of such problems but may for applications of sufficiently large roughness or Reynolds number (Re) be erroneous (Andersson et al. 2016). Particle Tracking Velocimetry (PTV) is a measurement method where, in this case, floating particles are photographed by a camera over an intended space and time. Software connected to the camera can then statistically determine the path of each individual particle, and hence determine the flow field for the fluid surface. Unlike PIV, particles used in PTV are usually larger and do not require illumination by a high-power light source, such as a laser. Hence, PTV allows the capture of a larger field of view (FOV) than PIV and may in certain applications be easier to implement, additionally, PTV is less sensitive to particle distribution compared to PIV. Acoustic Doppler Velocimetry (ADV) is a measuring technique where the subsequent doppler shift is measured from, in this case, four different positions relative to a small volume in the desired setup. The result is four measured, high frequency, velocity components (u, v, w1 and w2) of the flow in a small volume, averaged to a single point. Compared to PIV or PTV, ADV is a relatively intrusive method as it requires the measuring tool to be inserted into the desired medium. Typical particles required to operate this equipment includes zooplankton, air bubbles or sediment. Hence, in many applications no artificial particle seeding of the flow is necessary. ADV-systems have been employed to naturally rough waterways such as rivers (Buffin-Bélanger et al. 2006). Data from the previously mentioned study is used for validation in this study. The ADV-measurements will be applied to make sure that there are no disturbances at the inlet which can dramatically impact the results.

To ensure an evenly distributed random roughness the surface used is generated using the fractal-based diamond-square algorithm. Thereafter, the physical model is created using milling which, depending on resolution, in turn generates a discrepancy compared to the computer-generated model. The final physical model is laser scanned using a high-resolution laser scan to acquire a computer model as realistic as possible. The purpose of this study will be to jointly evaluate these systems. To do this the effects of inlet blockage in relation to relative surface roughness will be examined, as well as correlating roughness effects on the water surface in relation to water depth. The Reynolds number is defined as \( Re = \frac{Uh}{v} \), where \( h \) is the water depth and \( U \) is the centreline velocity double averaged both temporally and spatially (streamwise).
1.1. Dissipation

Dissipation plays an important role in flows over hydraulically rough surfaces. The dissipation ($\varepsilon$) at the wall ($y = 0$) is balanced by the viscous diffusion (Pope 2001)

$$\varepsilon = -\frac{\partial^2 k}{\partial y^2}$$

(1)

The introduction of surface roughness will lead to an increase in dissipation (Mansour, Kim, & Moin, 1988) which will result in a more efficient homogenization of the flow. Consequently, any perturbations induced by the inlet blockage will dissipate more rapidly in the vicinity of the rough surface and at lower depths. Hence, when modelling certain flows, such as relatively shallow rivers or tunnels of sufficient roughness, proper modelling of the surface roughness becomes increasingly important.

1.2. Pearson Correlation

The Pearson correlation coefficient will be applied to discern the correlation between the velocity component and the corresponding roughness height. Defined as

$$\rho_{u,k} = \frac{\text{cov}(u,k)}{\sigma_u \sigma_k}$$

(2)

$\sigma_u, \sigma_k$ is the standard deviation of the $u$-component of the velocity and the roughness height respectively.

2. Experimental Setup

The experimental setup consists of a flume, pump, two flow meters and a measuring system. The width of the channel is on average 1.2 meters and the length is 17.5 meters. The flat surface is placed at the height of the averaged height of the rough surface ($z=0$). The different water depths are controlled through an inclined plate at the outlet downstream of the flat surface. For even illumination of the flow, an LED ramp has been mounted above both the left and right edge respectively, visible in Figure 1.

![Figure 1. The flume with the LED ramp visible](image-url)

At the inlet of the flume a baffle was placed with three sheets. Two perforated sheets were placed upstream of a third sheet of honeycomb type, see Figure 2. The perforated sheets have a hollow radius of 2 and 1 cm respectively, while the honeycomb has a radius of 3 cm and a thickness of 29 cm.
To accurately determine the water depth, a depth gauge (see Figure 3) was placed at the outlet section. Hence, the water depth is measured relative to the average height of the rough surface. The term “height” refers to any instantaneous deviation from \( z=0 \). The final 1.5 meters of the flume is flat on all three surfaces and a part of the flat outlet section can be seen in Figure 3.

A right-handed coordinate system is implied throughout the experiments. The \( x \)-direction (\( u \)-component) is directed streamwise, the \( y \)-direction (\( v \)-component) is directed to the right of the flow-direction and the \( z \)-direction (\( w \)-component) is directed perpendicular to the bottom rough surface. The origin is placed at the middle of the end of the honeycomb, the average height (\( z=0 \)) is placed level with the lower flat outlet section. No \( w \)-component of the velocity is captured during the PTV measurements.

2.1. Particle Tracking Velocimetry

PTV is a non-intrusive method used for quantitative velocity measurements. In order to capture the flow, floating seeding particles are required. For this case, black particles provided by Sinfotek, with a diameter of 21mm were used. The specific weight of the particles were statistically measured to \( 6.18 \times 10^{-2} \text{g/cm}^3 \). Four cameras where roof mounted above the setup to capture the entirety of the flume. The cameras simultaneously capture a burst of 4 pictures each at 20Hz to produce one realization of the flow; this procedure was repeated for a total of 50 sets over 150s to produce a satisfactory temporal average. The resolution of the cameras is approximately 3 pixels/cm. To calibrate the PTV system, 4 points are placed in each cameras FOV to mark the measuring domain of each camera. Since the 4 domains have to be merged into one, the boundary points have to be chosen so that the neighboring domains always have 2 common points. The biased error associated with scaling from pixels to meters was estimated to be less than 1%; this was done by measuring over a known length. In PIV the primary source of error is
estimated to be 10% of the particle diameter in pixels (Balakumar et al. 2009). Using this reasoning, an estimated error of about 15% could be attained. Trial measurements of individual particles indicated that the actual error would likely be less than the one estimated; however, this PTV system is not to be taken as a precision tool.

2.2. Acoustic Doppler Velocimetry

ADV is a measuring technique rendering all three instantaneous velocity components at a small volume (point) at relatively high frequency using coherent Doppler shift. The measuring probe consists of one transmitter and four receivers; each receiver measures data for one velocity component, hence, the $w$-component will have two measured sets. These two sets are averaged into one set for the actual $w$-component. Compared to PTV, ADV is a relatively intrusive system since the probe has to be inserted into the fluid when measuring. However, the system is flexible as it requires no laser and usually no application of artificial seeding particles. Due to the spatial separation between the pulse pair transmitted by the velocimeter, at a specific distance above the surface the first signal reflected from the wall will collide with the second signal inside of the measuring volume. This is called a weak spot and results in interference, an instantaneous decrease in signal to noise ratio and a bad data point. For a flat surface the height of the weak spots can be predicted, however, the height of the surface used in this study is random and the wall will rarely be perpendicular to the incoming signal. Instead, the signal to noise ratio was monitored, and when a weak spot was identified the spatial separation between the signals was adapted accordingly to avoid this error. However, some bad data points are inescapable in proximity of the rough surface, to filter away these points an RC Filter, described in (Goring and Nikora 2002), was applied to the data. Due to the relatively large sample size, erroneous points could easily be removed without jeopardizing the temporal average of the velocity, which converges to a stable value at around 10000 points. No more than 3000 points were removed from any set, and usually only a handful of points were removed. The bias error is estimated to be less than 1% of the measured velocity. Measurements were conducted at 200 Hz for about two minutes. 15 cross sections were measured at different lengths downstream, 25 points were measured in each cross section. The ADV-measurements is restricted to the case of 50 cm with no inlet perturbations. For the ADV (50 cm depth) the Reynolds number is $\approx 120000$.

3. Results

Four different depths of water have been investigated, 50, 40, 30 and 20 cm relative to the average height of the surface roughness of the bottom wall. The flow rate was adjusted for each case to maintain a fairly constant inlet velocity throughout the experiments. The flow rates employed was 115, 96, 72 and 48 l/s. In Sec. 3.2 the correlation between the fluctuating velocity and surface roughness is investigated, $\langle k \rangle$ is the average height of the bottom rough surface and $k$ is the corresponding roughness height for the point and is attained from the laser scan. In Sec. 3.3 the correlation between surface roughness and perturbations of inlet blockage is examined. The flume was divided into 10 sections, within each section, the standard deviation of the $v$-component ($\sigma_v$) is calculated for each case of inlet perturbation and is compared to the case of no inlet perturbation. At a specific length downstream $\sigma_v$ for all cases will have converged and the inlet perturbations can no longer be traced, this length will henceforth be denoted the entrance length. Since the particles are floating and not evenly distributed in the flume no even velocity distribution was attained during the PTV measurements. Instead, every point measured will have an $x$, $y$, $u$ and $v$-component. An example of a measured set, at 20 cm depth and 25% inlet blockage, can be seen in Figure 4. This particular depth exhibits a significant disturbance from the surface roughness, visible on the water surface.
3.1. Rough Surface Model

For verification purposes, it is important that the roughness heights are distributed randomly to ensure that the spatially averaged roughness is uniform as well as reflecting natural and industrial roughness. The specific method used in generating the rough surfaces is the diamond square algorithm, a recursive sub-division algorithm often used to generate synthetic natural terrain (Fournier, Fussel, and Carpenter 1982). Since the algorithm is fractal in nature attributes such as self-similarity, which often can be found in natural settings, will also characterize the generated surface. A portion of the final generated surface used in the experiments can be seen in Figure 5.

For optimal verification of the experiments, the experimental setup is captured using a high resolution laser scan. One important factor for characterizing a rough surface is the Root Mean Square (RMS) roughness factor, which describes the fluctuations of surface height around the mean height. This roughness factor will be denoted $k_s$. For practical reasons, measuring head loss or boundary layer shearing ($\Delta U^*$) to determine the corresponding $k_s$ is not a realistic option in hydropower applications. Therefore, in this study the RMS roughness factor is calculated solely from the physical features of the surface, defined as

$$k_s^2 = \frac{1}{L} \int_0^L \langle f(h)^2 \rangle dh.$$  

This will serve as a length scale representative for the height of the surface roughness. To determine a longitudinal length scale, in addition to $k_s$, an autocorrelation function is applied in the streamwise direction to the laser scanned rough surface. The autocorrelation function is defined as

$$\langle R(r) \rangle_x = \frac{1}{k_s^2} \int_{-L/2}^{L/2} h(x)h(x+r)dx.$$  

The corresponding correlation function for the rough surface can be seen in Figure 6.

![Figure 6. Autocorrelation function applied to the flume](image-url)
The length-scale \( \tau_r \) is a measure of how far away two points can be on a random surface and still be considered correlated and represents the longitudinal size of the roughness elements on the surface. To determine \( \tau_r \) from the autocorrelation function is arbitrary and may vary from case to case. According to (Zhao, Wang, and Lu 2006) and (Zhang and Sundararajan 2005), the length is when the correlation has declined to 1/e of the original value. According to (Tennekes and Lumley 1972), the length-scale is the integral of \( \langle R(r)^2 \rangle \) from 0 to 1. In this case the difference between the methods is miniscule; hence, the former definition will be applied in this article. \( \tau_r \) for the walls are 0.0297 m for the left, 0.0352 m for the middle and 0.0319 m for the right respectively. \( \tau_r \) for the walls are 0.421 m for the left, 0.488 m for the middle and 0.383 m for the right respectively.

3.2. Height-Roughness Correlation

Naturally, at a sufficient water height any disturbances generated by the rough surface will have dissipated. In Figure 7 the roughness height-velocity correlation for the highest and lowest depth has been visualized.

![Figure 7. 50 cm (left) and 20 cm (right) water depth](image)

At 20 cm depth there is a clear correlation between the fluctuating velocity and roughness height. This effect could easily be visually determined as the aberrations on the water surface were pronounced for the low-depth cases. However, at 50 cm depth, there is no apparent correlation between \( u - \bar{u} \) and only ripples where seen on the water surface. To discern the remaining flow cases, the Pearson-correlation algorithm is applied to the data, as seen in Figure 8.

![Figure 8. Cross correlation between stream wise velocity component and the corresponding height, \( \tau_r \) is the longitudinal length scale for the rough surface.](image)

Figure 8 depicts a rapid linear decline of the \( u - \bar{u} \) correlation with an increase of depth, between 50 and 40 cm depth, the correlation has dropped by 71%. The 40 and 50 cm cases have similar correlation coefficients; hence, there is no clear correlation between \( u - \bar{u} \) already at 40 cm depth. This may also be an effect of the spatial shift of the surface perturbations relative to the rough surface, as the flow perturbations are transported downstream, while the correlation is performed between the roughness heights immediately below the measured point. The next part of the article will discuss detection of inlet perturbations and entrance length.
3.3. Inlet Perturbations

Randomness of the roughness affect the flow, consequently, the inlet effects are dependent on the position of the inlet blockage. This phenomenon has been visualized in Figure 9, where three different inlet blockage positions at a depth of 50 cm can be seen.

![Figure 9](image)

Figure 9. 50% inlet blockage at 50 cm depth from left, mid and right respectively

To account for this, all three inlet blockages are averaged into one profile for each depth. When all three profiles have approximately converged, then the effects of the inlet blockages have dissipated. This length will be denoted as the entrance length and is evaluated in Figure 10.

![Figure 10](image)

Figure 10. 50 (left) and 40 (right) cm depth

Figure 10 depicts inlet perturbations at 50 and 40 cm depth. By about 12 meters downstream the inlet blockages has converged and there is no substantial deviation between the cases. Additionally, a spatial variability of the water surface can clearly be seen in the cases without inlet perturbations. Further lowering the depth in the flume renders a decrease in entrance length, as seen in Fig. 11.

![Figure 11](image)

Figure 11. 30 (left) and 20 (right) cm depth
By 30 cm depth the entrance length is about 8 meters while for 20 cm that length has further decreased to about 7 meters, which is approximately a third of the flume or $D_s/L = 7$.

### 3.4. ADV-Measurements

As mentioned, the ADV measurements are performed at a depth of 50 cm and a flow of 0.115 m$^3$/s with no inlet perturbations. This corresponds to $Re \approx 120,000$, which is slightly lower than (Buffin-Bélanger et al. 2006) at similar conditions. Figure 12 depicts box plots of measurements from the centerline closest to the water surface.

![Figure 12](image)

**Figure 12.** Box plot of the centerline measurements closest to the water surface, the horizontal line represents the median, the box boundaries is the 25th and 75th percentiles and the whiskers represent the furthest data points not considered outliers.

Although no roughness-flow correlation could be detected for a depth of 50 cm using the PTV, a clear spatial variability can be seen using the ADV. The final three measured points show an increased dispersion for the sets. This coincides with the entrance length and may indicate that it has been reached by that point.

![Figure 13](image)

**Figure 13.** Turbulent kinetic energy at two cross sections, 2.0 (left) and 11.4 (right) meter downstream respectively. The blue line represents the water surface.

Figure 13 depicts the Turbulent Kinetic Energy (TKE) at two separate cross sections; the first one is close to the inlet (2 meters downstream) and the other one is positioned at 11.4 meters downstream. At the inlet the cross-sectional distribution of TKE is uniform, indicating satisfactory inlet conditions. The highest magnitudes of the turbulent kinetic energy are found along the rough surfaces, the largest being 1.423 Jm$^{-3}$. In Figure 14 a streamwise cross section is examined in a similar fashion as Figure 13.
Figure 14. Turbulent kinetic energy from the centreline, the blue line represents the water surface

The highest value of turbulent kinetic energy in the centreline is 0.613 Jm$^{-3}$; this is the fourth point from the top in the first row. Comparing the values to those of (Buffin-Bélanger et al. 2006) it is clear that they are slightly lower which likely is a consequence of the lower Re applied in this study. The behaviour, such as position of maximum turbulent kinetic energy, is in better agreement. The double averaged velocity of the PTV show a surface velocity of 0.284 m/s. Double averaging the ADV centre line velocity closest to the water surface show a velocity of 0.250 m/s. This is a discrepancy of almost 12% and is likely due to a combination of the uncertainty of the PTV and a slight miss calibration of the length scales for the PTV, which proved to be a somewhat arduous procedure since the cameras captured a vast FOV. Also, since the lengthwise sample size is much smaller for the ADV compared to the PTV, the double averaging process in itself might account for a part of the discrepancy.

4. Conclusions and Discussion

PTV and ADV measurements were applied to flow in a rough surface flume at 4 different water levels and 7 different flow situations on each water level. The systems used in this study differ in nature as PTV is based on measurements by camera and is able to capture large FOV. Additionally, the system does not sample uniform velocity distributions and therefore cannot be expected to provide in depth analysis of the flow when applied to larger systems. ADV on the other hand is based on Doppler shift and can perform high frequency measurements in a specific point, making mapping of larger systems grueling work. However, both systems have in common that they are logistically easy to apply and the PTV cameras could potentially be mounted on drones and natural particles such as wooden pieces could be applied for seeding. Results provided by joint measurements of the systems show good agreement both cross-platform and compared to other studies. A correlation between the bottom rough surface and the flow patterns could clearly be seen through the PTV for a depth of 20 cm, and 30 cm to a degree. Additionally, the inlet perturbations could successfully be traced using PTV for all depths and inlet perturbations. The surface roughness, as expected, proved to be very effective in eliminating inlet perturbations for lower depths. Accordingly, the surface roughness will not act solely as friction inducing in the classical sense; hence, proper modelling of the roughness is imperative for a realistic realization of the flow. The capture of this phenomenon by the systems was encouraging, and as a result the PTV and ADV could potentially be used to extract simple, yet important information from water systems to use as in-data for calculations. Further on, ADV-measurements should be performed on the flow-cases with inlet perturbations, as well as further validating the results by PIV or numerical simulations for example.
5. References


Gävunda: A case study

Authors:
L.R. Andersson, J.G.I. Hellström, P. Andreasson and T.S. Lundström

Manuscript
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L. R. Anderssona, J. G. I. Hellström, P. Andreassonb, and T. S. Lundströma

aLuleå University of Technology, SE-97187 Luleå, Sweden; bVattenfall AB, Research and Development, SE-81470 Älvkarleby.

ARTICLE HISTORY
Compiled October 29, 2018

ABSTRACT
The fluid dynamics within a water tunnel is investigated numerically using a RANS approach with the $k$-$\varepsilon$ turbulence model. The computational model is based on a laserscan of a water tunnel located in Gävunda, Sweden. The tunnel has a typical height of 6.9 m and a width of 7.2 m respectively. While the average cross-sectional shape of the tunnel is very even the local deviations are significant, where some roughness elements may be in the size of 5 m. The results indicate a pressure distribution highly dependent on the hydraulic radius of the tunnel. The average head loss through the tunnel can successfully be estimated using the Manning equation. This approach will filter out the spatial dependence of the pressure that is shown to be pronounced.

KEYWORDS
head-loss; case study; hydropower; rock tunnel; surface roughness;

1. Introduction

The hydropower industry experienced significant growth during the second half of the previous century. During this period, many tunnels were excavated for conveying water through turbines. Most of these tunnels are still used today, and studies have shown that many tunnels experience rock falls during their lifetime. A limited amount of rock falls within unlined hydropower tunnels are acceptable and largely unavoidable (Bråteit et al. 2016). In most cases it is a cost-benefit assessment where eventually the incremented friction losses become unacceptable and the tunnel has to be refurbished. It is not uncommon for tunnels to collapse, even after 30-40 years of usage (Reinius 1986). One reason for tunnel-instabilities is hydropoeaking, due to the increased uncertain production patterns in todays hydropower industry (Bråteit et al. 2016). Another theory is the localised flow effects arising due to the flow-roughness interactions. Studies such as Andersson et al. (2016, 2015) have shown increased localised fluctuations of pressure and velocity connected to roughness elements. Similarly, a study by Patel et al. (2017) shows that cyclic injection of a fluid into the rock walls leads to breakage at lower magnitudes of pressure than static injection. Roughness in the traditional industrial view, is usually considered as a tangential force acting on the wall i.e. friction. Its effects are regularly accounted for as a spatially averaged component (Jimenez 2004). While the net-effects on the flow due to the roughness might be correctly esti-
mated this way, the instantaneous effects are attenuated through spatial filtering.

It has been shown that many of the problems the tunnels experience may be connected to flow-roughness interactions (Andersson et al. 2018). Therefore it is of importance to be able to conduct a reliable risk assessment before commissioning of the tunnel and to understand the tunnel dynamics. The aim of this article is to apply previously developed theories to an actual case of an existing tunnel and to investigate the effect of varying hydraulic radius on the head loss.

In order to capture the geometry of the tunnel, a terrestrial laser scan with a resolution of 5 cm was applied, well enough to capture roughness elements of the smaller spectrum. This resulted in a point-cloud of about 10 million points. The points was turned into the final model using the software Imageware. A RANS approach with $k-\varepsilon$ model for turbulent closure was applied to the domain. RANS has been applied and validated in earlier research by Andersson et al. (2012) and it is well known that RANS under-predict shear layers and friction losses for similar cases. Even though the overall flow dynamics have successfully been validated, better agreement could probably attained with more advanced models, e.g. LES based models. For the objective of this study, RANS is believed to be sufficient.

2. Numerical setup

2.1. Gåvunda-tunnel

The tunnel studied here is located in Gåvunda, Sweden. The tunnel has a length of about 520 m, a typical width of 7.2 m and height of 6.9 m. The dimensions were statistically determined from measurements over a number of cross-sections of the tunnel. The inlet of the tunnel has a significantly larger cross-section as compared to the rest of the tunnel. The hydraulic radius of the inlet is about 2.1 m while the average hydraulic radius of the tunnel is 1.8 m. From the inlet, the tunnel contracts until about 60 m. From this until about 110 m the tunnel is relatively straight, whereby the bend stretches to roughly 410 meters. The length averaged hydraulic radius of the tunnel can be calculated according to

$$R_h = \frac{A}{P}.$$  \hfill (1)

In this equation $A$ is the cross sectional tunnel area and $P$ is the corresponding wetted perimeter. Both quantities are captured and averaged over 45 cross sections of the tunnel. The average hydraulic radius for the tunnel is $R_h = 1.825$ m. A rough schematic of the tunnel can be seen in Fig. 1.

The roughness of the tunnel can be described to be of random nature with seemingly random large scale elements, sometimes in the size of 5-7 m, existing along the rough surface. Some of these roughness elements may be a result of localized rock falls (Bråteit et al. 2016) but also originating from the blasting of the tunnel. The majority of the largest roughness aberrations are located at the outer wall of the curve, which is consistent with the position of maximum velocity and shear of a bend.

A typical discharge through the tunnel is 45 $m^3/s$, which results in a bulk velocity of $U \approx 1$ m/s. The resulting Reynolds number $Re = 4R_h U/\nu \approx 7.3$ million. Tunnel excavation is done with an intended ideal even form and area. However, in reality the
finished tunnels will always have a local hydraulic radius varying with length. This variation is pronounced as visualized in Fig. 2 a) where the instantaneous hydraulic radius is shown in relation to the tunnel length.

Figure 2. a) The local hydraulic radius as a function of the tunnel length. The black line represents the average. b) 45 cross sections of the tunnel. The red line represents the average cross section.

Figure 2 b) show 45 cross sections along the tunnel. The local variations in cross sectional area is evident. Interestingly, the average cross section is surprisingly "ideal" given the longitudinal irregularities, and obviously it is a crude estimate to parametrise these geometrical deviations from the ideal shape by a single roughness height value.

To turn the point-cloud obtained from the scanning into a workable surface the commercial software Imageware was used. This was done by dividing the tunnel into sections and each section into four different walls. Subsequently, planes were adapted to each wall with an average point to plane error of $\approx 0.5\%$. The planes were transferred to ICEM CFD, where they were further trimmed and the problems due to software conversion addressed. ICEM CFD was also used to generate the final mesh used in the numerical simulations.
2.2. Determining rough surface statistics

Due to the tunnel being non-linear in all coordinates, it is problematic to isolate specific sections of the tunnel. The first step is to establish a centreline of the tunnel, an example of the tunnel and corresponding centreline can be seen as the red line in Fig. 3 a).

Every 10 cm a new plane is defined normal to the centreline, ensuring that the planes are perpendicular to the flow direction. All points within 10 cm of each planes are averaged length-wise as \((\bar{x}, \bar{y}, \bar{z})\). Each point in each transect are then transformed to polar coordinates and is thereafter angularly averaged with a span of 1 degree according to \((\bar{x}_\theta, \bar{y}_\theta, \bar{z}_\theta)\). Each 10 cm section of the tunnel, as well as any given section of the walls may now by this transformation be accessed. The point cloud had blank areas which the laser scanning had missed. These areas were generally small but few areas were in the range of 1 m. The lengthwise averaging span was chosen to account for the majority of these blank spots. The resolution of the point cloud also has to be taken into consideration when choosing the proper averaging span. It should be noted that the bend of the tunnel is omitted during this visualization. To quantify the roughness height of the walls the RMS roughness factor \((k_s)\) is introduced according to (Sarkar and Dey 2010) and (Bråtveit et al. 2012)

\[
k_s = \sqrt{\frac{1}{n} \sum_{i=1}^{n} k_i^2}.
\]  

\(n\) is the sample size and \(k_i\) is the relative height of the point. \(k_s\) is calculated to 0.7163 m, which is representative of the roughness height of the surface. Using the same expression the RMS cross sectional area \((A_s)\) is calculated to 13.3 m². To establish the longitudinal lengthscale \((\tau_r)\) of the largest roughness elements on the tunnel a spatial auto-correlation function \(L_{\tau_r}(x)\) is introduced (Zhao et al. 2006). \(\tau_r\) is then attained from integrating \(L_{\tau_r}(x)\) from 1 to 0, resulting in \(\tau_r = 29.82\) m.
2.3. Discretization and simulation setup

The domain was discretized into smaller subgrid domains using the commercial software ICEM CFD v.15. The walls of the domain had a tetra mesh size of 0.3 m while the elements close to the rough surface was refined to a maximum size of 0.1 m, rendering a mesh size of approximately 120 million elements and 21 million nodes. In this study, one deciding factor for choosing the appropriate numerical model was the computer cost, even at a relatively coarse mesh the computational cost becomes problematic. Numerically the k-\(\varepsilon\) model is relatively cheap compared to e.g. LES and it is known to capture the main flow behaviour for similar applications (Andersson et al. 2012). The wall roughness was fully resolved and not modelled, as shown important by Andersson et al. (2015, 2016).

3. Results and Discussion

An overline e.g. \(\overline{x}\) denotes quantities averaged length-wise of the tunnel, while a prime e.g. \(x'\) denotes fluctuating quantities. Angle brackets e.g. \(\langle x \rangle\) denote temporally averaged quantities. \(\theta\) denotes angular averaging. A line is defined as running along the centre, from the inlet to the outlet of the tunnel. This line was used to sample the static pressure and this data will be labelled by “Line” in the legends. 30 planes was placed evenly spaced along the tunnel perpendicular to the flow direction, these planes were used to determine the area-averaged static pressure and the velocity along with several geometrical parameters. The Pearson correlation between the hydraulic radius and the static pressure is defined according to (Råde and Westergren 2004)

\[
\rho_{\text{Rh}, p_s} = \frac{\text{cov}(\text{Rh}, p_s)}{\sigma_{\text{Rh}} \sigma_{p_s}}.
\]

(3)

(cov) denote the covariance of the two variables and \(\sigma\) denotes the standard deviation of the given variable. The result of the algorithm varies between -1 and 1. The method can be used to evaluate the linear correlation between two given variables.

3.1. Head loss

The head loss is measured along a line placed at the centre of the tunnel going from the outlet to the inlet, see Fig. 4. Additionally, the static pressure is area-averaged over each of the 30 cross sections placed in the tunnel. This data is represented by the diamonds in Fig. 4.

Aside from two points the spatially averaged value of the static pressure coincide well with the pressure measured along the line. In river engineering it is common practice to estimate flow resistance parameters according to the Manning equation (Chanson 2004), defined as

\[
U = \frac{1}{n} R_h^{2/3} S_f^{1/2}.
\]

(4)

Where \(S_f\) is the gradient of the friction line defined as \(- \frac{1}{\gamma p} \frac{dp}{dx}\) and \(U = Q/A\). The ideal case in Fig. 4 is calculated using Eq. 4, assuming constant \(R = 1.825\) m and
Figure 4. The solid line represents the pressure measured at the centre of the tunnel, while the dotted line represents the ideal case with no variation in hydraulic radius. The data represented by diamonds is the static pressure averaged over the cross-sections $A = 48.290 \, m^2$. $n$ is calculated from the measured head loss to be 0.022 and $Q = 45 \, m^3/s$, both will be assumed constant throughout this article. From Fig. 4 it is clear that the Manning equation is a good estimation of the overall head loss through the tunnel. This is however dependent on the quality of the input data as the hydraulic radius ($R_h$) is difficult to measure and rarely remain constant in real cases. Figure 5 a) show the head loss from the Manning equation taking into account the instantaneous change in hydraulic radius, while Fig. 5 b) details the relation between hydraulic radius and head loss.

At about 150 m and onwards the variations increase with length, this coincides with larger instantaneous changes in hydraulic radius and the direction of the tunnel. This is a clear indicator of the inhomogeneity of the tunnel cross-section. The dependence between static pressure and hydraulic radius, especially for the large variations, is clearly depicted in Fig. 5 b). Figure 6 show the velocity, averaged length-wise and in time within the tunnel.

The double averaged velocity profile for the tunnel show an un-even behaviour throughout the tunnel, although the perturbations appear to mainly stem from the bend in-
stead of solely from the roughness as indicated by Andersson et al. (2018, 2016). Thus, the strain caused on the walls may be larger on the outward wall of the bend.

4. Conclusions and Discussion

Simulations were performed on a tunnel whose cross section was captured using terrestrial laser scanning. The results show a significant localised variation of hydraulic radius along the tunnel. Despite the significant longitudinal cross sectional irregularities of the tunnel, the average cross section is surprisingly smooth and symmetric. While overall head loss could successfully be predicted using the Manning equation i.e. assuming constant hydraulic radius. The instantaneous variations with respect to hydraulic radius would not be accounted for and the resulting estimation would be crude. The same dynamic can be seen in the length-wise average velocity profile, which has an uneven distribution. Although the surface roughness has an impact on the velocity, the largest perturbations appears to stem from the bend. It would be of scientific value to produce an experimental setup based on this tunnel. Important factors to investigate would then be the impact of Reynolds number on the flow situation as well as the validity of the \( k-\varepsilon \) turbulence model. At a certain threshold, localized velocity effects due to the roughness would become large enough to manifest in the double averaged velocity and at that point one could start to suspect that the regional fluctuations could initiate rock fall processes or worse given time. One of the largest problems encountered was correct handling of the scanned tunnel data. No software, in our possession, proved sufficient in effectively managing all aspects of the processing from point-cloud to surface to finished mesh with acceptable precision. As a consequence, two different softwares had to be involved to individually deal with each step leading to further problems. The problem was solved by meticulous work in each step to assure the following step had near perfect in-data. The main problems appear to stem from the co-planarity of the points provided and from the tunnel not being constant in any coordinate, due to the bend. As shown in earlier research the \( k-\varepsilon \) has a tendency to under-predict the head loss for similar cases. While the RANS approach likely captured the main characteristics of the flow, the actual dependence of the hydraulic radius would likely be higher in the real case.
Acknowledgement(s)

The research presented was carried out as a part of "Swedish Hydropower Centre - SVC". SVC has been established by the Swedish Energy Agency, Energiforsk and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University. www.svc.nu. The authors would also like to acknowledge Magnus Svensson and Fortum for providing the geometry of the laser scanned tunnel.

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