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Numerical Investigation of a Hydropower Tunnel: Estimating Localised Head-Loss Using the Manning Equation

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Abstract: The fluid dynamics within a water tunnel is investigated numerically using a RANS approach with the k-ε turbulence model. The computational model is based on a laser scan of a hydropower tunnel located in Gävunda, Sweden. The tunnel has a typical height of 6.9 m and a width of 7.2 m. While the average cross-sectional shape of the tunnel is smooth the local deviations are significant, where some roughness elements may be in the size of 5 m implying a large variation of the hydraulic radius. The results indicate that the Manning equation can successfully be used to study the localised pressure variations by taking into account the varying hydraulic radius and cross-sectional area of the tunnel. This indicates a dominant effect of the tunnel roughness in connection with the flow, which has the potential to be used in the future evaluation of tunnel durability. ANSYS-CFX was used for the simulations along with ICEM-CFD for building the mesh.

Keywords: head-loss; case-study; hydropower; rock tunnel; surface roughness; ANSYS-CFX

1. Introduction

The hydropower industry has 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 [1]. There is a cost–benefit assessment where eventually the accumulated 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 [2]. One reason for tunnel instabilities is hydropeaking, due to the increased uncertain production patterns in today's hydropower industry [1]. Another theory is the localised flow effects arising due to the flow–roughness interactions. Studies have shown that increased localised fluctuations of pressure and velocity are connected to roughness elements [3,4]. Similarly, a study on hydraulic fracturing shows that cyclic injection of a fluid into the rock walls leads to breakage at lower magnitudes of pressure compared to static injection [5]. Roughness from a traditional industrial point of 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 [6]. While the net effects on the flow due to roughness might be correctly estimated this way, the effects of local variations are lost through spatial filtering.

It has been shown that, indeed, the roughness may have a dominant effect on the flow in the tunnel i.e., the flow parameters are highly dependent on where you measure inside of the tunnel [7]. In this work, the relation between the static pressure and the cross-section of the tunnel is evaluated.

This opens possibilities for relations such as the Manning's equation to be used as a measure of the localised pressure fluctuations. Such an investigation would only require knowledge of the tunnel geometry and an average friction term, thus, enabling easier and more reliable risk assessment studies.

To perform this, data from an actual hydropower-tunnel has been used. In order to capture the geometry of the tunnel, a terrestrial laser scan with a resolution of 5 cm was applied, meaning that roughness elements of the smaller spectrum were captured. This resulted in a point-cloud of about 10 million points. The points were turned into the final model using the software Imageware. A methodology for extracting tunnel data from the point cloud is also developed. A RANS approach with k-ε model for turbulent closure was applied to the domain. RANS has been applied and validated in earlier research [8] 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 the next logical step would be either an experimental model or a more advanced numerical model, e.g., LES-based models. However, since the goal of this study is to generate average values, it is not certain that more advanced models would render more reliable results than RANS-based models.

2. Numerical Setup

2.1. Gävunda-Tunnel

The tunnel studied here is located in Gävunda, Sweden. The tunnel has a length of about 517 m, a typical width of 7.2 m and a typical height of 6.9 m. The dimensions were statistically determined from measurements over a number of cross-sections of the tunnel. The tunnel is always fully submerged and no free surfaces are present inside 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 m. The length averaged hydraulic radius of the tunnel can be calculated using

$$R_h = \frac{A}{P} \tag{1}$$

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 resulting in an average hydraulic radius $R_h = 1.825$ m. A rough schematic of the tunnel can be seen in Figure 1.

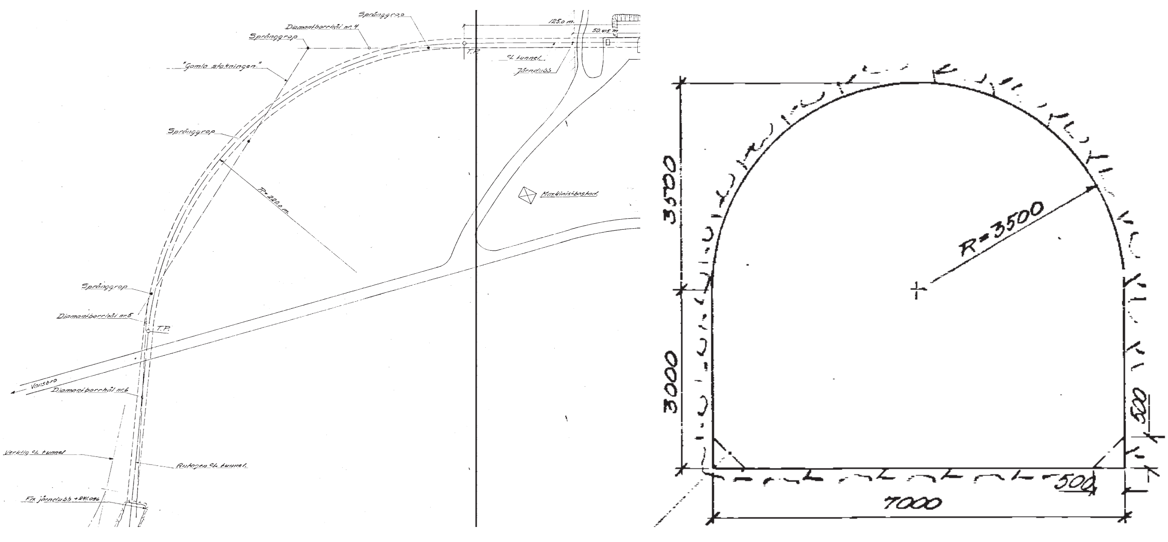


Figure 1. A top-view (**left**) and cut-through (**right**) schematic of the tunnel, both drawings made pre-excavation. The flow is from right to left according to the left figure. Units are given in m.

The roughness of the tunnel can be described to be of random nature with seemingly random large scale elements, sometimes in the lateral size of 5–7 m, existing along the rough surface. Some of these roughness elements may be a result of localized rock falls [1] 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 $Re = 4R_hU/\nu \approx 7.3$ million. Tunnel excavation is generally 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 Figure 2a where the localised hydraulic radius is shown in relation to the tunnel length.

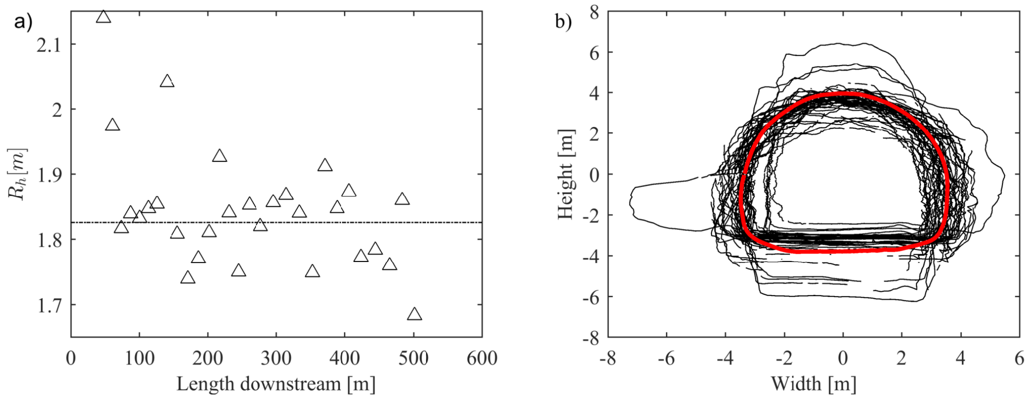


Figure 2. (**a**) The local hydraulic radius as a function of the tunnel length. The black line represents the average. (**b**) 45 cross sections of the tunnel. the red line represent the average cross section. Section 2.2 details the procedure on how to attain data on the cross sections.

Figure 2b shows 45 cross-sections along the tunnel. The local variations in cross-sectional area are evident. Although the average-cross section is surprisingly "ideal" given the longitudinal irregularities, it is obviously a crude estimate to use the ideal shape with a single roughness height value to derive head-loss and variations of pressure.

To turn the point-cloud 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 walls with an average point to plane error of $\simeq$0.5%. The planes were transferred to ICEM CFD, where they where 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 or extract any useful data. The first step is to establish a centreline of the tunnel; an example of the tunnel and corresponding centreline can be seen in Figure 3a. Note that 75% of the points have been omitted for visibility purposes in the figure.

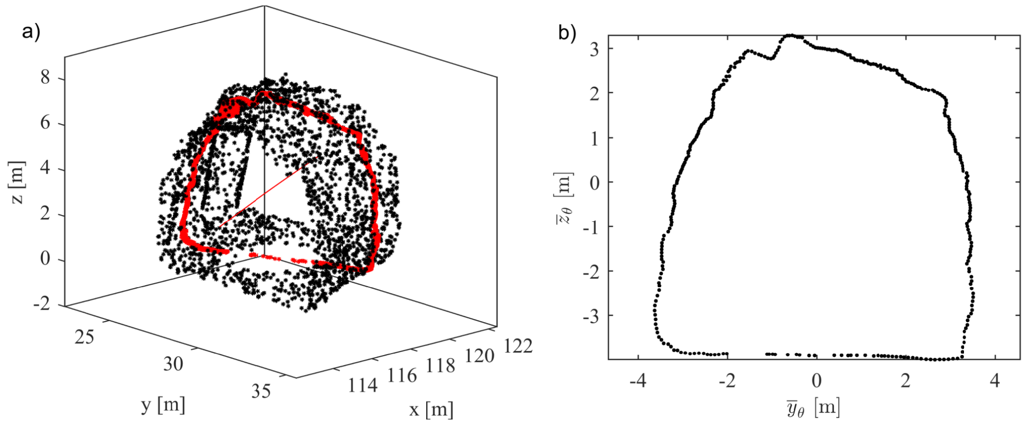


Figure 3. (**a**) depicts a section of the tunnel. The black points represent the point-cloud, the red points are all points within 0.10 m of the perpendicular plane, the red line is the centreline of the tunnel. (**b**) depicts the cross section resulting from averaging the red points in (**a**).

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 plane are averaged length-wise as ($\overline{x}$,$\overline{y}$,$\overline{z}$). Each point in each transect are then transformed to polar coordinates and is, thereafter, angularly averaged with a span of 1 degree according to ($\overline{x}_\theta$,$\overline{y}_\theta$,$\overline{z}_\theta$). Each 10 cm section of the tunnel, as well as any given section of the walls, may now by this transformation be accessed, see Figure 2a. The point cloud had blank areas which the laser scanning had missed. These areas were generally small but a few of them 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 [9,10]

$$k_s = \sqrt{\frac{1}{n}\sum_{i=1}^{n} k_i^2} \tag{2}$$

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 m^2. To establish the longitudinal lengthscale (τ_r) of the largest roughness elements on the tunnel a spatial auto-correlation function $L_{\overline{x}_\theta}(x)$ is introduced [11]. τ_r is then attained from integrating $L_{\overline{x}_\theta}(x)$ 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 element close to the rough surface was refined to a maximum size of 0.05 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. The mesh size was, however, chosen after a brief convergence study. The total head loss of the tunnel where modelled using 4 different mesh sizes, the difference was less than 5% for the final two mesh sizes. Despite the mesh convergence, the resulting y^+ is relatively high, with an average of slightly above 600 for the final mesh and below 800 there was little change in the flow behavior. The extremes range from 10 to 1500 depending on the position of the tunnel wall. Earlier studies [7,8] have shown that the majority of the frictional losses come from the large scale roughness, hence, numerical wall-functions will have a small effect on the resulting flow. Numerically, the k-ε model is relatively cheap compared to e.g., LES and it is known to capture the main flow behaviour for similar applications [8]. The wall roughness was fully resolved and not modelled, as shown by [3,4]. The inlet flow was set to 45 m^3/s with an outlet condition at the other end. The software used for solving the RANS equations was ANSYS CFX v15.

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. x_θ denotes angular averaging. With static pressure, the authors mean that there is no dynamic pressure involved. 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. The line is constant in the z-direction, so there is no change in potential pressure to take into account; 30 planes were placed evenly spaced along the tunnel perpendicular to the flow direction, these planes were used to determine the area-averaged static pressure (denoted with diamonds in the figures) and the velocity along with several geometrical parameters. Reliable tunnel data, such as cross-sectional area and hydraulic radius were extracted from the laser-scan using the methodology described in Section 2.2. The Pearson correlation for the hydraulic radius and static pressure is defined according to [12]

$$\rho_{p,AR^{2/3}} = \frac{cov(p, AR^{2/3})}{\sigma_p \sigma_{AR^{2/3}}} \tag{3}$$

(cov) denote the covariance of the two variables and σ 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.

Head Loss

The head loss is sampled along a line placed at the centre of the tunnel going from the outlet to the inlet, see Figure 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 Figure 4.

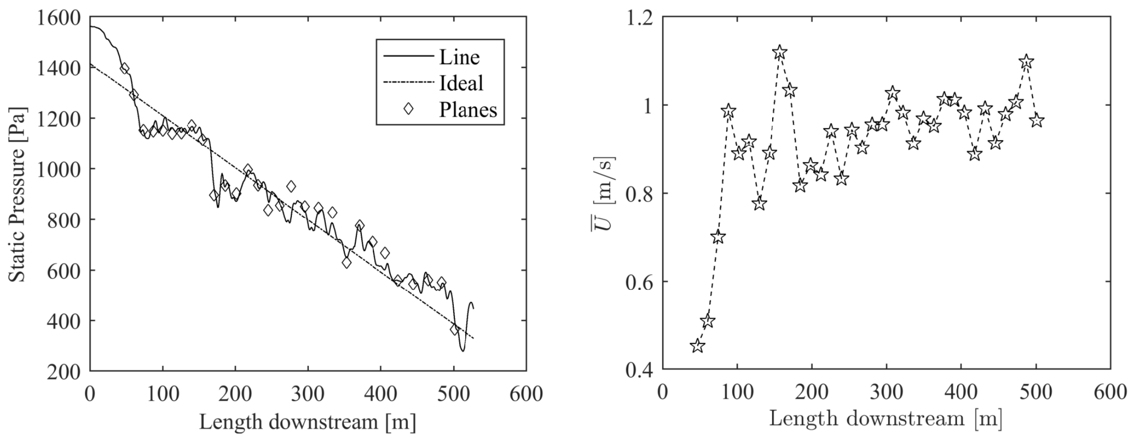


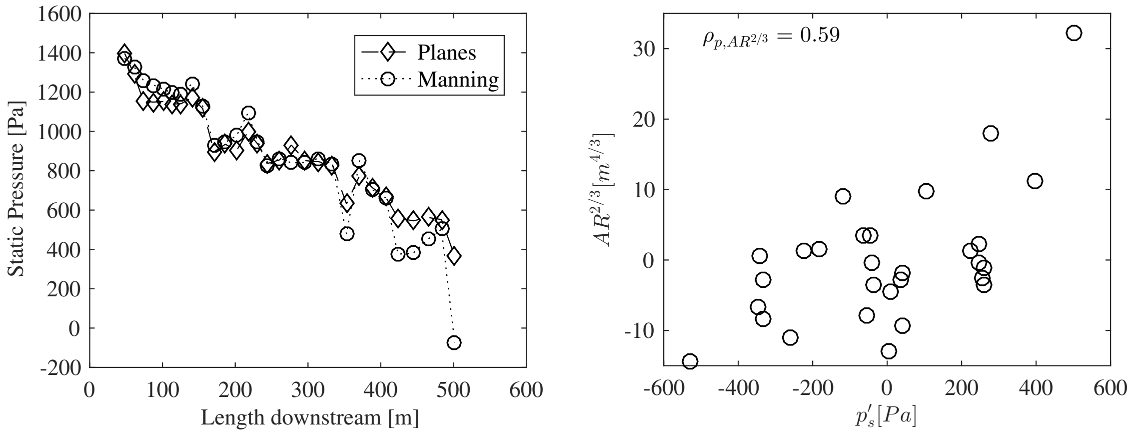
Figure 4. (**Left**) the solid line represents the pressure modelled at the centre of the tunnel, while the dotted line represents the ideal case with no variation in hydraulic radius. The data represented by diamonds is the static pressure area-averaged over each of the cross-sections. (**Right**) area averaged velocity from the entrance to the outlet of the tunnel.

Aside from two points the spatially averaged value of the static pressure coincide well with the pressure modelled along the line. This means that the roughness has a dominating effect on the bulk flow and methods based on the cross-section e.g., Manning or the energy equation should capture most of the fluctuations as long as the variations of A and R are taken into account.

In river engineering it is common practice to estimate flow resistance parameters according to the Manning equation, defined as [13]

$$U = \frac{1}{n} R_h^{2/3} S_f^{1/2} \tag{4}$$

where S_f is the gradient of the friction line defined as $-\frac{1}{g\rho}\frac{dp}{dx}$ and $U = Q/A$. The ideal case in Figure 4 is calculated using Equation (4), assuming constant $R = 1.825$ m and $A = 48.290$ m^2, this is how a typical measurement would be done "in the field". n is calculated from the acquired head loss to be 0.022 and $Q = 45$ m^3/s, both will be assumed constant throughout this article. From Figure 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. The next step is to apply Equation (4) to calculate the head loss while taking into account the varying factor $AR^{2/3}$. The equation is in effect solved incrementally to calculate the resulting head-loss between each individual plane, implying a spatial averaging of about 17.2 m which is shorter than the longitudinal length-scale τ_r. The result can be seen in Figure 5a, while in Figure 5b the correlation between p_s and $AR^{2/3}$ is detailed.



(**a**) (**b**)

Figure 5. (**a**) The circles represent accumulated head loss estimated using Equation (4) and the diamonds are from Figure 4. (**b**) The static pressure as a function of hydraulic radius, $\rho_{p,AR^{2/3}}$ represents the Pearson correlation coefficient.

The negative pressure at the final point in Figure 5a is due to the very sharp contraction of the outlet; see Figure 2a. The Manning equation appear to over-estimate the head loss where the largest variations in hydraulic radius occur. The agreement between the pressures are nevertheless good, and the Manning equation provides a good estimate of the localised pressure. Figure 5b show a high correlation between the pressure and $AR^{2/3}$, this is as theorized due to the dominating effect of the roughness on the flow. It can be concluded that the manning equation has unexploited capabilities when evaluating the localised variations in pressure.

4. Conclusions

Simulations were performed on a hydropower tunnel whose cross section was captured using terrestrial laser scanning. Much like the schematic of the tunnel, the average cross section is smooth and symmetric. The localised variations are, however, significant and are shown to have a dominant effect on the flow inside the tunnel. Despite this, the Manning equation proved to be a good estimation of the total head loss within the tunnel. This would leave out any localised pressure fluctuations, but is useful for extracting friction-related quantities from the mean flow. Additionally, it is shown that the relation can also be used to predict the localised pressure fluctuations by taking into account the varying hydraulic radius and cross sectional area of the tunnel. This methodology involves incrementally calculating the head loss between given cross sections of the tunnel. While the agreement was good, for the largest cross sectional variations of the tunnel, this method appears to over-estimate the head loss. The reason for this is unclear, however, as shown in earlier research, the k-ε has a tendency to under-predict the head loss for similar cases. Hydropower tunnels are a very hostile environment to measure within and very few methods exist for monitoring the structural integrity during operation. By far, the most popular method involves bringing the tunnel out of operation, removing the water and visibly inspecting the walls. The reported results are, therefore, encouraging as pressure measurements might provide new possibilities to evaluate rock falls during operation.

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-ε turbulence model. 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. Additionally, an algorithm was created to extract tunnel data directly from the point-cloud. The main problem appears to stem from the co-planarity of the points provided and from the tunnel not being constant in any coordinate, due to the bend.

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