Converting wall roughness to hydraulic roughness in fully turbulent pipe flow: Small-scale experiments and large-scale measurements at the Kárahnjúkar HEP, Iceland

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Introduction

The paper reports on small-scale laboratory experiments of pressurized turbulent pipe flow. The work was motivated by the study of the hydraulic roughness of the 40 km long unlined TBM bored headrace tunnel of the Kárahnjúkar HEP in Iceland. An extensive measurement program was conducted during the excavation of the tunnel to calculate hydraulic roughness of the tunnel walls and thus obtain accurate predictions of head loss and power generation. The HEP started operation in November 2007. Since then, measurements have shown that the head loss, based on roughness measurements, had been overestimated by approximately 10 %. The laboratory experiments were conducted in 2010 on one hand to elucidate the relationship between measured physical roughness of tunnel walls and hydraulic roughness, but also to follow up the measurements at the Kárahnjúkar HEP.

The laboratory experiments were scaled with the Reynolds number of the flow and the relative roughness of the interior of the pipes, such that the flow was in a fully turbulent state. The dimensions of the pipes were fixed while the internal roughness changed between setups. The experiments comprised both direct measurements of pressure drop through the straight pipes and back-calculations of the pressure drop from the measured roughness of the pipes. The roughness was measured with a high accuracy laser scanner. Five different procedures were used to convert the measured roughness to a hydraulic roughness coefficient. Comparison of the calculated and measured pressure drop was used to determine the best fitting procedure for the conversion. It is generally regarded that hydraulic roughness is some function of the height, spacing, density and shape of the physical roughness for a given flow type. The experiments were thus also designed to test the sensitivity of the measured head loss to the height/depth of the roughness elements relative to the pipe diameter and the spacing between the roughness elements.

The experimental results indicate that the chosen procedures can be used to convert measured roughness to hydraulic roughness. The results are furthermore consistent with results from measurements at the Kárahnjúkar HEP. The small-scale experiments indicate that the best fitting method for the conversion depends on the characteristics of the roughness, *i.e.:* the depth of the roughness elements; whether the roughness elements are cut into a surface or extend out of the surface; and also, but to a lesser extent, the distance between the elements. More experiments are needed to clarify this.

1. Background

1.1 Head loss estimates for the Kárahnjúkar headrace

The Kárahnjúkar HEP is located on the east coast of Iceland. The headrace tunnel is 40 km long, of which 35.5 km were full-face TBM bored, with diameters 7.2 and 7.6 m. Three TBMs were used in the project, as shown on Fig. 1. Operation of the HEP started in November 2007.

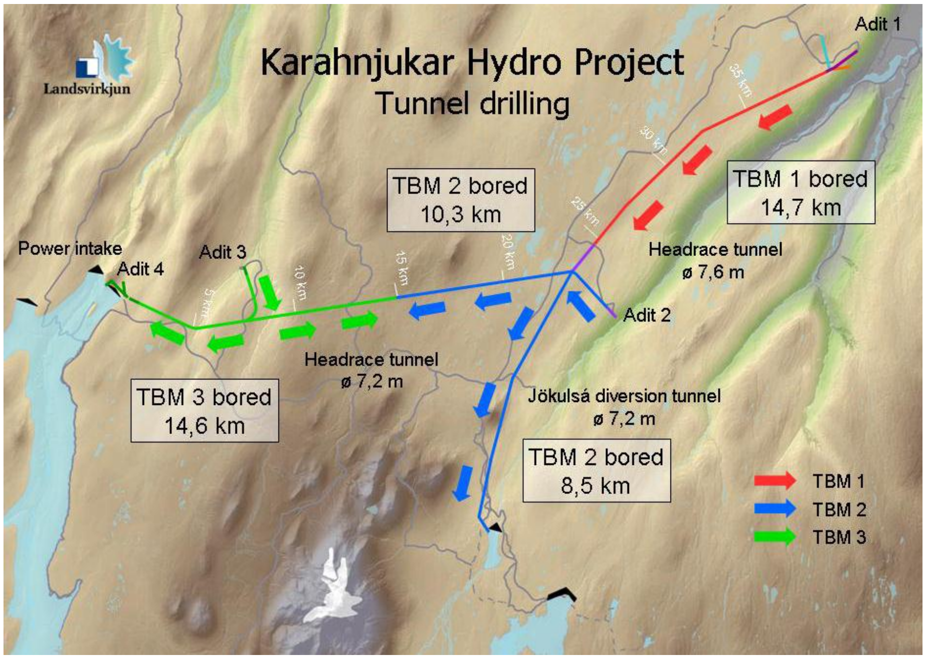

Fig. 1. Layout of the headrace tunnel of the Kárahnjúkar HEP, east Iceland. Three TBMs (1, 2 and 3) were used to bore the 7.2 and 7.6 m wide circular tunnels.

Design estimates for head loss along the tunnels were based on rough estimates of the hydraulic roughness of TBM bored tunnels in volcanic rock. Refined estimates of the hydraulic roughness were made during the construction of the tunnel. The estimates involved elaborate inspections of the tunnel walls and high accuracy laser scans of approximately 10 % of the inspected areas. Hydraulic friction factors for the different rock types in the tunnel were derived and later verified with actual head loss measurements along the pertinent tunnel. These measurements provided an important assessment on the calculated values of the friction factors. The measurements showed that the total head loss (approx. 75 m at the design discharge of 144 m^3s^{-1}) had been overestimated by some 10 %. It was concluded that the calculated hydraulic friction factors of relatively smooth rock types in the tunnel (sedimentary rock and porphyritic basalt) were well determined in the study, while the values at the rougher end of the scale (shotcrete, pillow lava, cube jointed basalt and olivine basalt) were not as well determined.

The measurement program is described in detail by Hákonardóttir et al. (2009) and in a detailed report (Landsvirkjun, 2009). The weakest link in the methodology adopted at Kárahnjúkar involved the conversion from a measured physical roughness profile to a hydraulic roughness coefficient.

1.2 Theory

The head loss, H_L along a uniformly rough pipe of length l and diameter d is given by the Darcy-Weisbach equation;

$$H_L = \left(f\frac{l}{d} + \Sigma_j K_j \right)\frac{u^2}{2g} = h_f + h_k, \qquad (1)$$

where, g is the gravitational acceleration, u is the average flow speed, f is the Darcy-Weisbach friction factor and K is a factor accounting for singular losses. Surface roughness has an effect on frictional resistance and the friction factor, f is a function of the interior pipe roughness. The effect is negligible for laminar pipe flow, where the height scale of roughness elements is smaller than the thickness of the viscous sublayer. In fully rough flow, the sublayer is totally broken up and friction is independent of the Reynolds number. The friction factor is well documented for different commercial surfaces (*e.g.* steel and concrete) but less so for more irregular surfaces, such as unlined conveyance tunnels (*e.g.* headrace tunnels of hydropower plants). The flow state in such tunnels is commonly fully turbulent.

Hydraulic roughness may be linked to measured roughness through Nikuradse´s equivalent sandgrain roughness k_s, which is related to the Darcy Weisbach friction factor by the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k_s}{3.71d} + \frac{2.51}{\mathrm{Re}\sqrt{f}} \right), \qquad (2)$$

where Re is the Reynolds number and d is the pipe diameter. The sandgrain roughness, k_s is the diameter of uniform sand grains, glued to the interior of the pipes (Nikuradse, 1940).

A slightly different approach involves calculating the Darcy-Weisbach friction factor directly from the standard deviation, σ of a roughness profile by Heerman's equation (1968):

$$\frac{1}{\sqrt{f}} = 4.285\log_{10}\left(\frac{D_h}{\sigma^{1.66}}\right) - 8.798. \qquad (3)$$

Heerman (1968) derived the equation by connecting measured average velocity in turbulent pipe flow to theoretically derived shear velocity. His experiments involved air flowing through 0.1 m wide pipes of different roughness. Heerman tested the importance of spacing between individual roughness elements by systematically changing the wave length of the interior sinusoidal roughness in the pipes. He measured the head loss at Reynolds numbers in the range 10^4 to 10^5. The amplitude to pipe diameter values ranged from 0.01 to 0.08. The wavelength to amplitude ratio ranged from 4 to 120.

Both approaches, (2) and (3), involve converting uniform roughness to hydraulic roughness. However, the roughness of tunnel walls is by no means uniform. It is generally regarded that hydraulic roughness is some function of the height, spacing, density and shape of the physical roughness for a given flow type (a fixed Reynolds number and pipe roughness). Pegram and Pennington (2006) suggest three approaches for calculating one representative height scale, h from a measured non-uniform roughness profile, by means of the *equivalent sinusoid* of the profile, h_σ, and the *mean range height* of the profile, h_λ.
The equivalent sinusoid, h_σ is taken as twice the amplitude, a, of the equivalent sinusoid fitted through a roughness profile. The amplitude depends only on the standard deviation of the roughness profile, but not on the wave length of the sinusoid and is given by

$$h_\sigma = 2a = 2\sqrt{2}\sigma\,. \qquad (4)$$

The mean range height, h_σ is calculated by averaging the differences between maxima and minima within intervals of the centroidal wavelength, λ, *i.e.* for a roughness profile $x(t)$, where $0 \le t \le T$ (T = number of points in the profile),

$$r_i = \max\left[x_i, x_{i+\lambda}\right] - \min\left[x_i, x_{i+\lambda}\right], \quad 1 \le i \le T-\lambda.$$

and

$$h_\lambda = \frac{1}{T-\lambda}\sum_{i=1}^{T-\lambda} r_i\,. \qquad (5)$$

2. Experimental setup and design

2.1 Design

The small-scale laboratory experiments were designed to determine the Darcy-Weisbach friction factor, f for fully developed, fully turbulent pressurized flow in pipes from measured roughness of the interior of the pipes. The experiments were scaled with the Reynolds number of the flow and the roughness of the interior of the pipes, relative to the pipe diameter. They involved direct measurements of pressure drop and discharge through straight, 7.5 m long and 0.07 m wide pipes. The internal roughness of the pipes differed between setups.

The internal roughness of each setup was measured accurately with a laser scanner and the pressure drop calculated for a given discharge rate through the pipes using five different methods, A – E:

A. Heerman's semi-empirical equation (3).
B. The Colebrook-White equation (2) with $k_s = h_\sigma$.
C. The Colebrook-White equation (2) with $k_s = 2h_\sigma$.
D. The Colebrook-White equation (2) with $k_s = h_\lambda$.
E. The Colebrook-White equation (2) with $k_s = 2h_\lambda$

The measured pressure drop was finally compared with the pressure drop calculated from the roughness scans in order to identify the best fitting method (A - E) for the conversion.

2.2 Laboratory setup

The experimental setup consisted of three components: A 0.4 m^3 constant head tank, a 6.0 – 7.5 m long and 0.07 m wide pipe and a 0.4266 m^3 tank downstream of the pipe, see Fig. 2. The water level in the constant head tank was regulated by an overflow spillway. The floor of the tank was lined with a sponge to stabilise the surface. A 1.54 m drop from the tank to the horizontal pipes was used to drive $(6 – 8) \cdot 10^{-3}\ m^3 s^{-1}$ of water through the pipes. The pressure was measured at four locations along the pipe as shown on Fig. 2. A manometer was used to measure the pressure drop over 5 m, with an accuracy of ± 1 mm (typically H_L = 0.2 – 0.6 m), and two piezometers located between the manometer measurements for control. The downstream tank was used for discharge measurements, derived from accurate filling time of the tank. The water was stabilized by lining the tank´s floor with sponges. The accuracy of the deduced flow speed was 0.05 m s^{-1}.

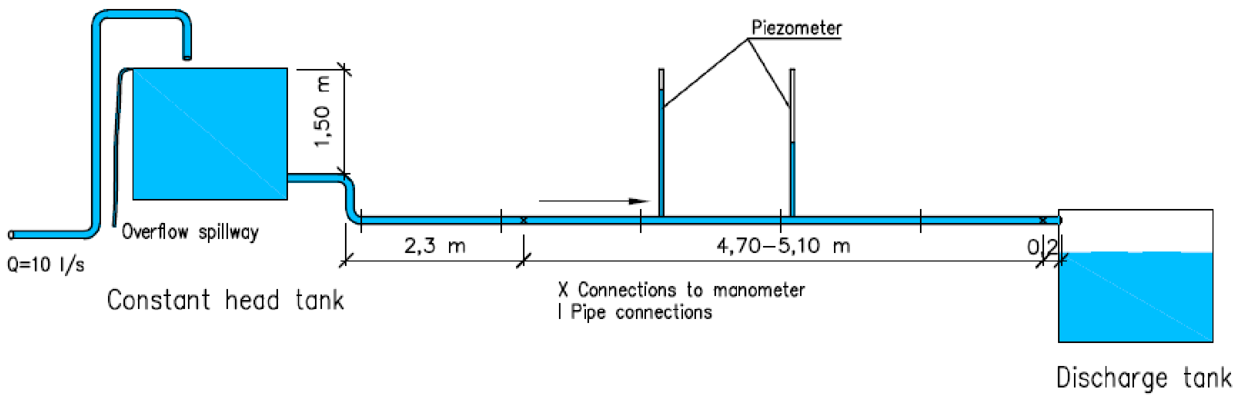

Fig. 2. A schematic diagram of the experimental setup.

The internal roughness of the 7.5 m long and 6.92 mm wide PCV pipes was crafted by cutting the pipes into five 1.5 m long segments. Each piece was roughened by brushing its interior with a steel brush, fixed to a drill with a 1.5 m long shaft. This created a random base roughness on the scale of 0.1 – 0.5 mm. 1 – 2 mm deep spiral grooves separated by 7 – 14 mm were additionally carved into the pipe surfaces. All of the five 1.5 m long pipe pieces comprising each experimental setup had exactly the same interior roughness. The segments were connected using flanges (see Figl 2).

A different type of interior texture was created using a mixture of sand and paint. The diameter of the sand was in the range 1 – 2 mm. The pipes were initially steel brushed and then filled with a mixture of sand and acryl paint twice, with a week long drying period between each coating. Finally a coating of pure paint was applied.
The equivalent diameter of the sand roughened pipe was 6.76 mm. The diameter was determined by filling it with water, weighing the water and calculating the equivalent diameter of the pipe from the known length and density of the water. The six different experimental setups of rough pipes are shown on Fig. 3.

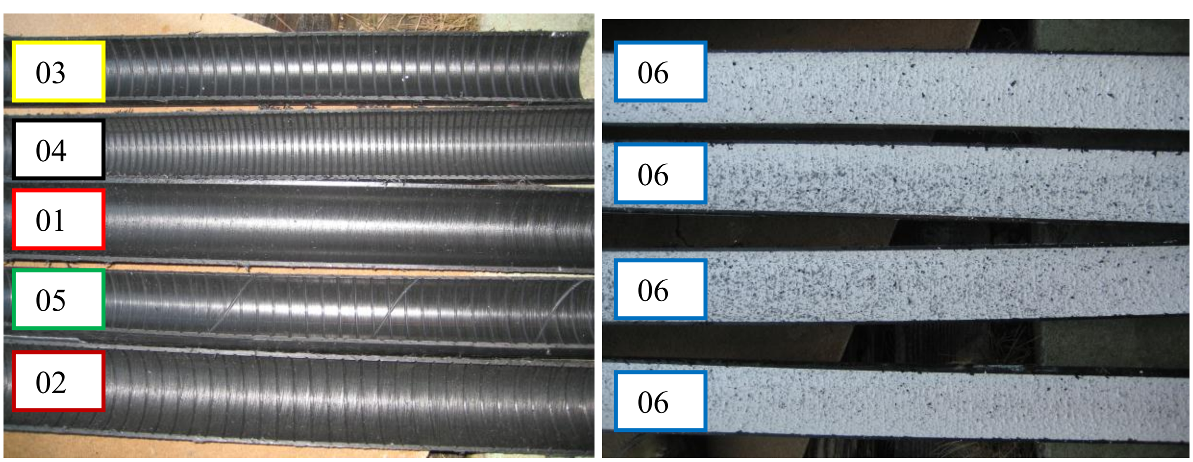

Fig. 3. Photographs of the interior of the 0.07 m wide pipes in setups 01 - 07.

2.2 Laser scans

One pipe segment from each setup was cut in half, length wise, and the interior of one of the halves scanned with a high accuracy laser. The interior roughness of the sand roughened pipe was not completely uniform, thus four pipe halves were scanned (see Fig. 3). The pipes were scanned with a portable coordinate measuring machine (Faro Scan Arm), see Fig. 4. The same Scan Arm is owned by Pöyry Infra Ltd. in Zurich in Switzerland and was used in the Kárahnjúkar headrace tunnel (Landsvirkjun, 2009). The instrument scanned 0.04 m wide and approximately 0.8 m long strips. The coordinates were scanned with an accuracy of 0.1 mm and point spacing of less than 0.25 mm. Special software (PolyWorks V.9.0.7 from InnovMetric Software Inc.) was used to evaluate the scanned data, running on a Panasonic Notebook CF29. Four profiles with a vertical separation of 8 mm were extracted from each scanned strip.

Fig. 4. The laser scan arm scanning the pipes.

3. Results

3.1 Head loss measurements

The Darcy-Weisbach friction factors for each pipe setup were calculated according to equation (1). Singular losses due to the four pipe connections in each setup were determined from initial runs in one long smooth pipe and in the same smooth pipe that had been cut into four segments and connected (see Fig. 2). The coefficient of singular losses was back calculated as $K = 0.03$ for each connection, adding up to 0.020 m for the four connections at the typical discharge rate of $8{\cdot}10^{-3}$ m^3 s^{-1}. The singular losses were roughly 10 % of the frictional losses along the smooth pipe.

The back-calculated friction factors, f are shown on Fig. 5. One notes that all but the control run, D, are within the rough turbulent zone. For comparison, a range of the hydraulic friction in the Kárahnjúkar headrace tunnel is shown. Flow in the tunnel is also within the rough turbulent zone for typical discharge rates between 20 and 144 m^3 s^{-1}.

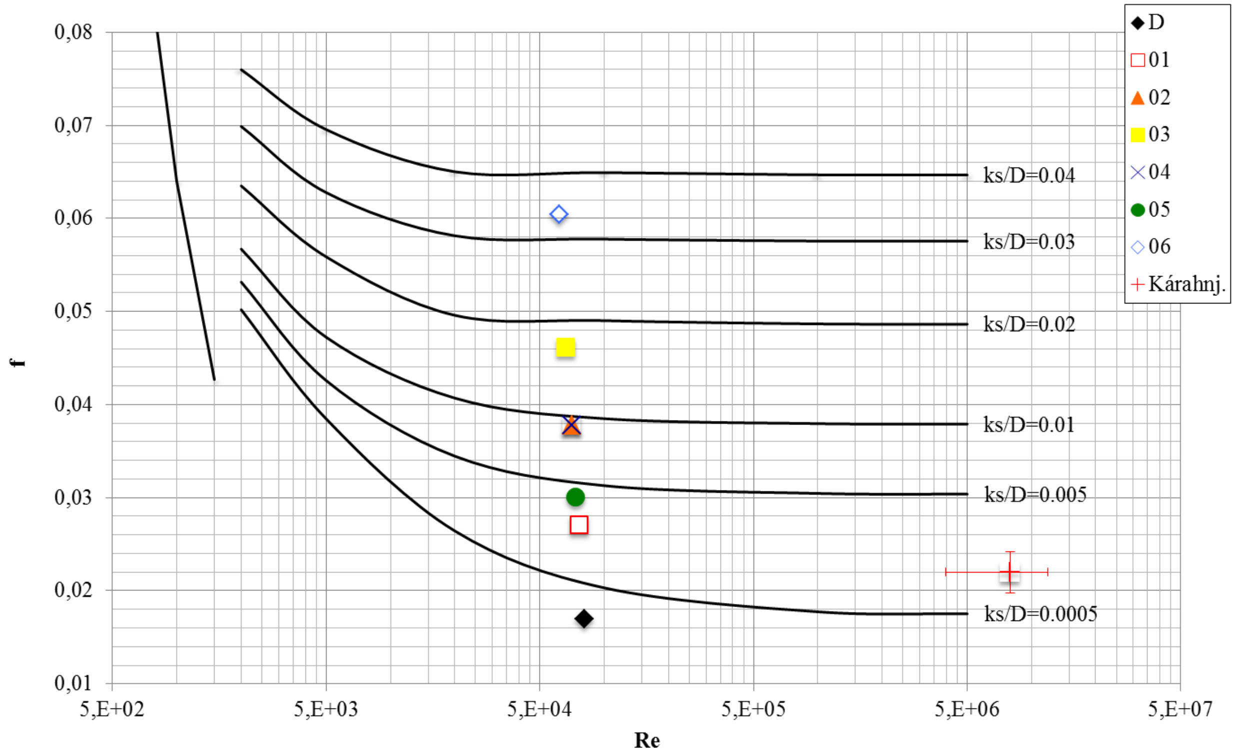

Fig. 5. The hydraulic friction factor, f as a function of the Reynolds number for each experimental run (D, 01 - 06) and the Kárahnjúkar headrace tunnel.

One notes that the friction factor increases with deeper spiral cuts ($f_{01} < f_{05} < f_{02} < f_{03}$). Setups 03 and 04 differed by the distance between cuts (see Fig. 3). Interestingly, the friction factor does not increase as the distance between the grooves is halved, from 12 to 6 times the depth of the cuts ($f_{02} \sim f_{04}$). The pipes in setup 06 were roughened with sand of similar grain size as the depth of the cuts in setup 03. The largest friction factor was derived for that pipe setup.

3.2 Laser scans and head loss calculations

The interior of one pipe half in each setup was scanned and four profiles extracted from each scan, see Fig. 6. Horizontal parts of each scanned profile were analysed, since the pipes were slightly. The Darcy Weisbach friction factor was calculated for each roughness profile using five different procedures (A – D), outlined in Section 2.1. The accuracy of the scans was tested by scanning one of the pipes' halves twice. The resulting profiles were identical and calculations yielded precisely the same friction factors.

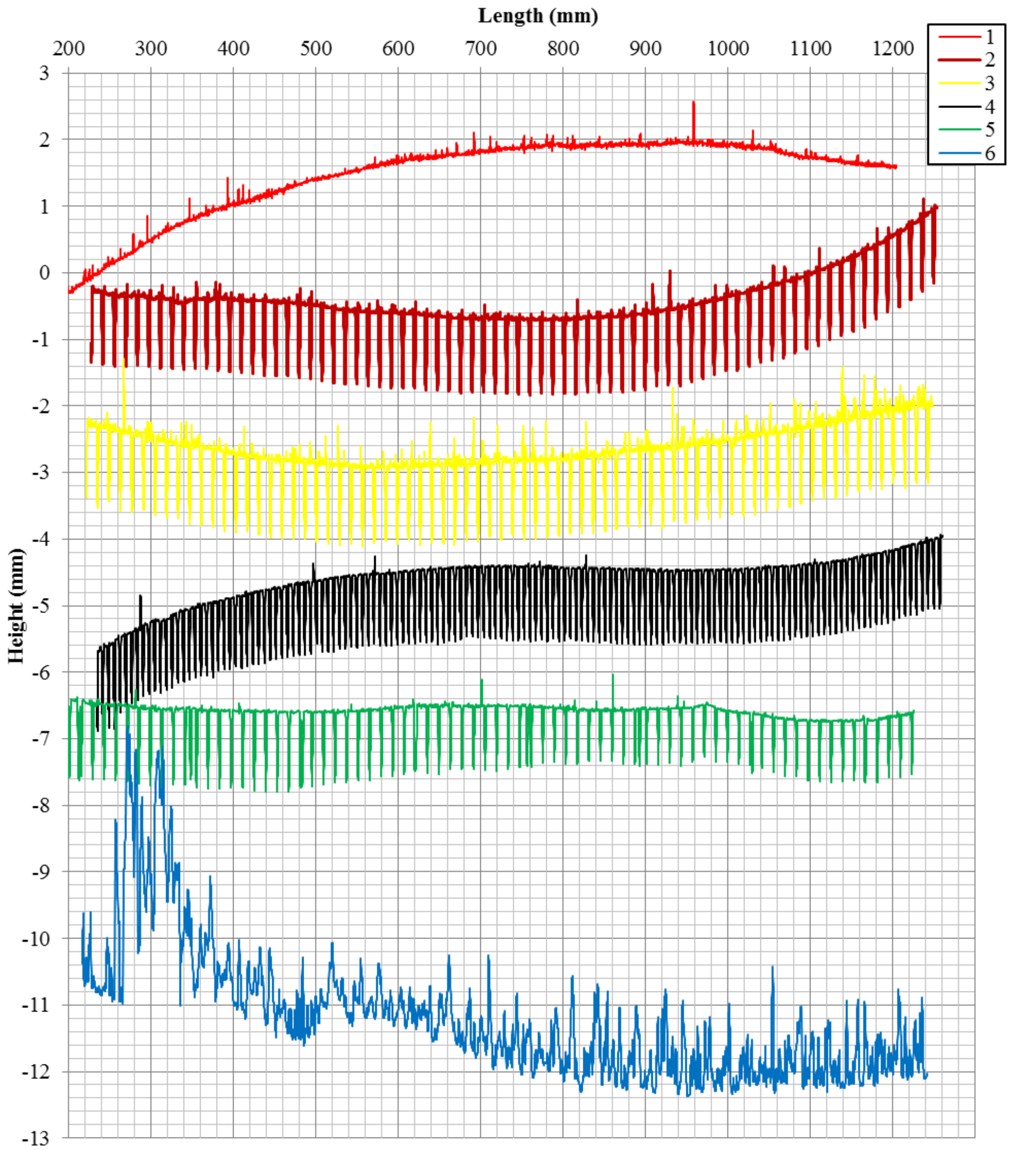

Fig. 6. One out of four scanned pipe profiles for setups 01 - 06.

3.3 Comparison

The hydraulic friction, *f*, is plotted in Fig. 7 for methods A – D and compared with the back-calculated hydraulic friction from the measured head loss, H_L, in experimental setups 01 – 06. One notes that methods A (Heerman´s equation) and D yield the lowest friction values, while method B always yields higher values than method D (standard deviation vs. mean range height). Method C yields the highest friction values.

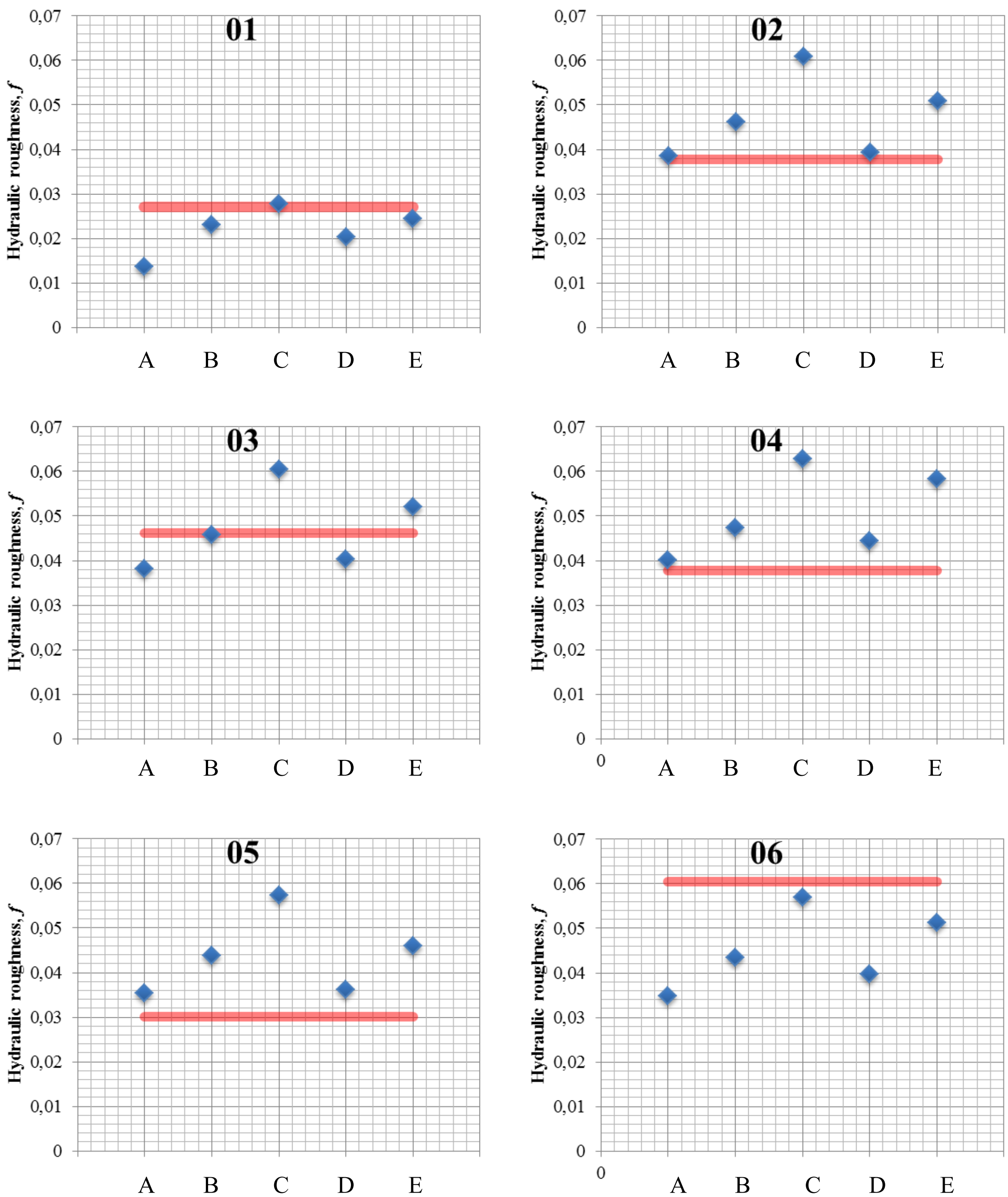

Fig. 7. The hydraulic friction, f calculated from the laser scanned profiles using methods A, B, C, D and E (diamonds) and the hydraulic friction derived from the measured head loss(red line) for experimental setups 01 – 06.

The Colebrook-White equation with $k_s = h_\lambda$ (method D) and Heerman´s equation (method A) correlate best with the hydraulic friction in setups 02 – 05. Method C (the Colebrook-White equation with $k_s = 2h_\sigma$) best agrees with the hydraulic friction values in setups 01 and 06.

This difference may relate to the different character of the roughness in these setups. The interior roughness of the pipes in setups 02 – 05 is dominated by one or two height scales with a constant interval, while setups 01 and 06 contain more random roughness elements (depth and distance between the depths, as shown on Fig. 6). Another distinct difference exists between setups 01 and 06, and 02 – 05. The roughness elements in setups 01 and 06 move in and out of an average pipe surface, while the roughness elements in setups 02 – 05 are dominated by cuts into the pipe surfaces.

These results indicate that the proposed methods (A – E) can be used for calculating hydraulic roughness from a measured roughness profile. Which method may depend on the characteristics of the roughness. The experimental results show that the height scale (size) of the roughness elements is more important than the spacing between these up to a certain value of the depth relative to the distance between the elements. More experiments are needed to determine the exact distance.

4. Kárahnjúkar wall roughness

The headrace tunnel of the Kárahnjúkar HEP is mainly excavated through basaltic rock formations of olivine basalt and porphyritic basalt, with a considerable amount of scoria and scoracious basalts. Some 35% of the tunnels traverse sedimentary rock, predominantly sandstone and conglomerate. The igneous rock formations in the tunnel were considerably rougher than the sedimentary rock, see Fig. 8.

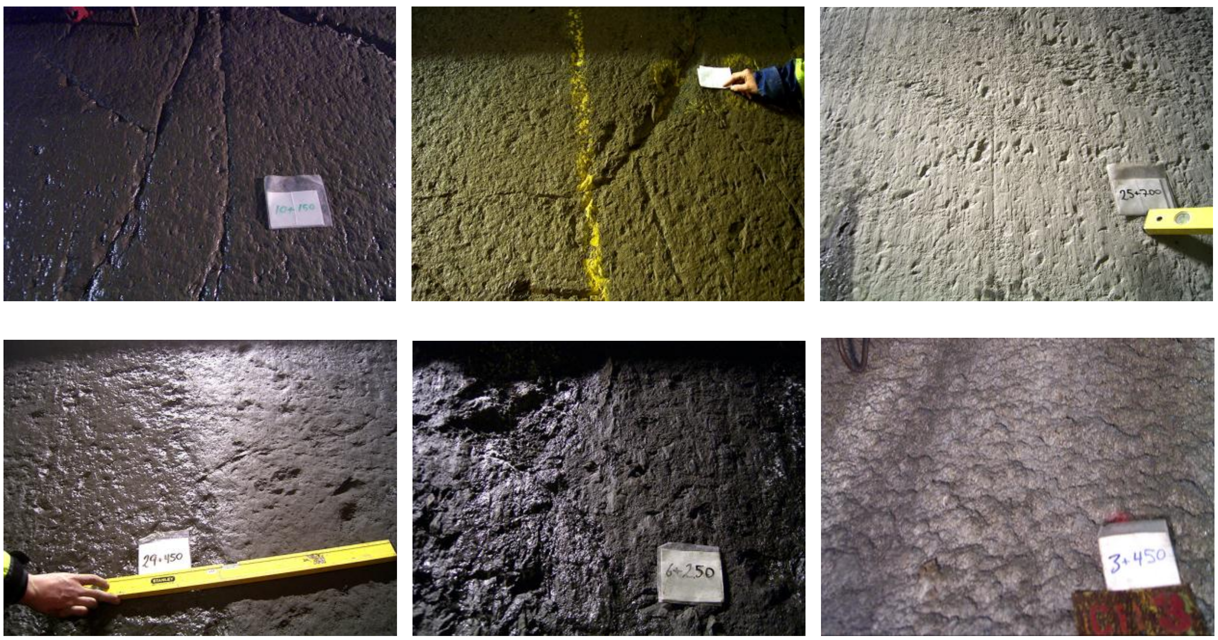

Fig. 8. Photographs of medium rough tunnel walls of porphyritic basalt, olivine basalt, sandstone, scoria, cube jointed basalt and shotcrete, from top left to bottom right, respectively.

As noted above, head losse along the Kárahnjúkar headrace tunnel was calculated according to equation (1). Method D was applied to calculate the hydraulic friction, *f* of the tunnel walls from laser scans of the tunnel walls (Hákonardóttir et al., 2009). The calculations were compared with measurements of head loss at different locations along the headrace tunnel, following the start-up of the HEP in 2007. The total head loss in the headrace tunnel was approximately 10 % less than the calculated head loss. It was deduced that differences between measured and calculated head losses were largest along tunnel reaches with large amounts of rough shotcrete, and with a relatively large amount of rough and heavily jointed unlined surfaces.

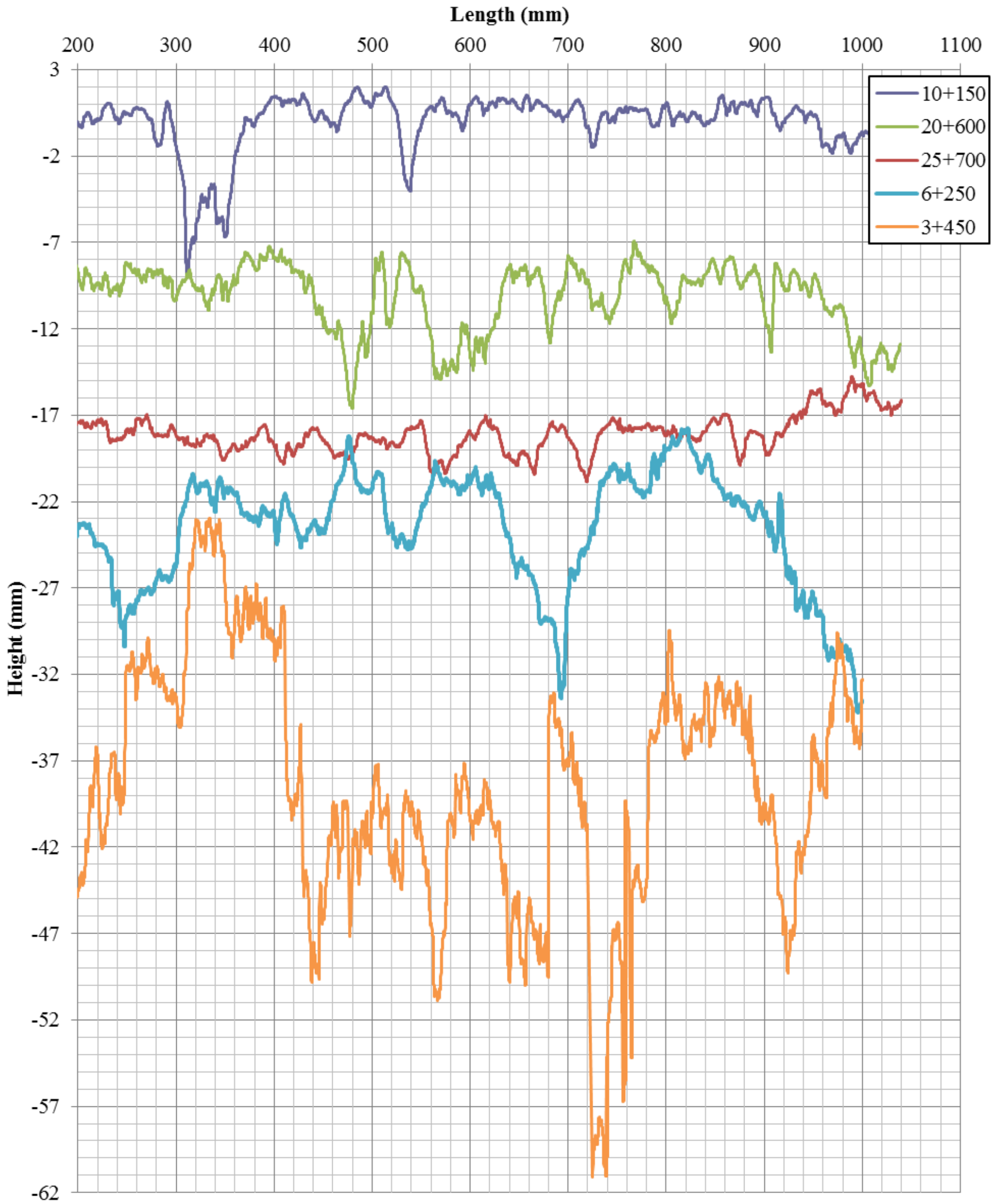

Fig. 9. Scanned tunnel wall profiles for medium rough: porphyritic basalt (10+150); olivine basalt (20+60); sandstone (25+700); cube jointed basalt (6+250); and shotcrete (3+450).

The results are consistent with the results in experimental runs 02 – 05. The experimental results indicate that the best fitting method for converting the roughness profiles to a hydraulic roughness coefficient depends on the the characteristics of the surface irregularities (small scale roughness and joints). The best method may thus depend on the tunnel wall geology of the unlined headrace tunnel. Examples of roughness profiles for different rock types of geologies in the Kárahnjúkar headrace tunnel are shown on Fig. 9.

5. Conclusions and future work

Comparing the calculated and measured head loss in the small-scale pipe experiments yielded similar results as the comparison of measured and calculated total head loss along the Kárahnjúkar headrace tunnel when the roughness of the pipe walls had one dominating frequency. The best fitting method to calculate the hydraulic friction involved using the mean range height of a roughness profile as Nikuradse's equivalent sandgrain roughness (method D). The method (and also Heerman´s equation, method A) predicted the lowest values of the hydraulic roughness and lead to a slight overestimate of the head loss. Conversely, the method yielding the highest hydraulic roughness values using twice the standard deviation of a roughness profile as Nikuradse´s equivalent sandgrain roughness was found to fit best for surfaces of a more random wall roughness height and spacing.

The experimental results suggest that the methodology adopted at the Kárahnjúkar HEP for calculating hydraulic roughness of TBM bored tunnel walls, from laser scans of the walls, can be applied in future tunnelling projects. They furthermore confirm the deduced hydraulic roughness values for volcanic rock types observed along the headrace tunnel and reported by Hákonardóttir *et al*. (2009). However, the laboratory experiments pose further questions regarding the importance of the spacing between the roughness elements and whether these elements are moving into or out of an average surface.

Additional questions concerning the validity of the derived hydraulic friction values for different types of turbulence in pipe flow, *i.e*. quasi turbulent flow vs. rough turbulent flow have not been addressed. Quasi turbulent flow may be observed along headrace tunnels of HEPs that are not operated at full discharge rates. This is however not of a great concern since design and production estimates of HEPs commonly depend on maximum head losses occurring at maximum/design discharge rates.

References

1. **Hákonardóttir, K.M., Tómasson, G.G. and Stefánsson, B**. "The hydraulic roughness of unlined and shotcreted TBM-bored tunnels in volcanic rock: In-situ observations and measurements at Kárahnjúikar Iceland", *Tunnelling and Underground Space Technology*, doi: 10.1016/j.tust.2009.07.007, 2009.
2. **Landsvirkjun**, "Roughness measurements & head loss estimates, Kárahnjúkar waterways", Report, LV-2009/012, February 2009.
3. **Nikuradse, J.**, "Laws of flow in rough pipes", *Petroleum Engineer*, 1940. Washington: NACA.
4. **Heerman, D.F.**, "Characterization of Haydraulic Roughness", thesis submitted in partial fulfilment of requirements for PhD. Colorado State University. Colorado, 1968.
5. **Pegram, G.G.S., Pennington, M.S.**, "A method for estimating the hydraulic roughness of unlined bored tunnels", Report, Water Research Commission by the Department of Civil Engineering, University of Natal, WRC Report No 579/1/96. ISBN No. 1 86845 219 0, 1996.

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