The Southern African Institute of Mining and Metallurgy
SHOTCRETE FOR AFRICA

HYDRAULICS OF SHOTCRETE TUNNEL LININGS,
(vis-à-vis other linings)

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Cradle of Human Kind, Misty Hills Hotel
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TOPICS FOR DISCUSSION:

- Setting the Scene
- Risk & Uncertainty related to Sizing of LHWP Delivery Tunnel, based primarily upon Ageing Phenomena
- Existing Reference Projects:
  - Orange-Fish Tunnel: Concrete Lining Ageing Phenomena
  - Inanda-Wiggins Tunnels: Unlined Bored Tunnel Hydraulic Roughness (the start of Univ. of Natal’s “Pegram & Pennington” Laser Scan research)
  - Lesotho Highlands Water Project: Delivery Tunnel Ageing Phenomena
- New Reference Projects:
  - Kárahnjúkar Headrace Tunnel (Iceland) Hydraulic Roughness predictions, based upon the Pegram & Pennington research (from ITT publication)
  - Chimay D&B Headrace Tunnel (Peru): (excerpt from Electrowatt-Ekono sponsored research paper)
- Pegram & Pennington Laser Scan Approach to Hydraulic Roughness Prediction
- Photos: Delivery Tunnel Concrete and Unlined Sandstone
- Conclusions & Recommendations

Note: Fully Rough Turbulent Formulae (Darcy-Weisbach, plus “conversions”)

\[
\text{Head Loss } h = \lambda \left( \frac{L}{D} \right) \left( \frac{v^2}{2g} \right) \text{ with } \frac{1}{\lambda} = (2 \log 3.7 \frac{D}{k})^2 \text{ and } n = \lambda^{\frac{1}{2}} \frac{D^{1/6}}{11.15}
\]
Tunnel Roughness Concepts Diagram

1. Q – Tunnel capacity.
2. v - Flow velocity.
4. Tunnel diameter.
6. Quality of construction.
7. Instrumentation design.

1. Flow Regime.
2. Influence on lining ageing of flow regime – rough/smooth turbulent flow.
3. Modification of ageing characteristics.
4. Quality of construction.
5. Data capture and analysis.

References
1. The literature and,
2. Orange Fish Tunnel.
3. LHWP Delivery Tunnel.
4. London Ring Main.
5. Umgeni Water tunnels.
6. CIRIA.
7. CSIR.
9. DWAF.
10. University of Stellenbosch models.

Origin: Draft SANCOT 2000 Guidelines
2. DECISION MAKING PROCESSES

2.1 General

Operational research decision theory views decision making as a continuum between decision making under certainty through decision making under risk to decision making under uncertainty. (Reference 1)

<table>
<thead>
<tr>
<th>Certainty</th>
<th>Risk</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Deterministic)</td>
<td>(Probabilistic)</td>
<td>(Random)</td>
</tr>
</tbody>
</table>

2.2 Decision making under certainty

This represents conventional engineering computation where the outcome of each alternative can be calculated with certainty. In hydraulics an example would be the sizing of a measuring weir to measure a known maximum flow so as to optimize, for example, approach channel cross sectional area against head loss. The minimizing of waste in cutting a number of metal shapes out of a single sheet is another example. Linear programming techniques can be used to optimize such decisions.

2.3 Decision making under risk

Under this scenario the implicit assumption is made that for each possible alternative the probability of occurrence is known.

The basic procedure for decision making under risk consists of

(a) Enumeration of all possible outcomes by means of a decision tree

(b) Calculation of the expected value of each alternative in the group

(c) The criterion for the best alternative is based on the highest Expected Monetary Value Criterion.

Whilst the techniques are simple they are not widely used because of a -

(i) lack of familiarity with the concepts

(ii) unwillingness to move from dealing in supposed certainties to the realm of probabilities

(iii) paucity of records, in many instances.
2.4 Decision making under uncertainty

In this case -

(i) the outcome from each alternative is judged to be so uncertain as to preclude assigning a risk probability to it.

(ii) the decision between alternatives will turn upon what is known as the 'risk utility' of the owner.

"Risk utility" means to what extent the owner is willing to gamble upon the effects of any particular outcome, that is, to incur a future reward (or penalty) as a result of a present outlay (or failure to make that outlay, in the case of a future penalty).

Most people are risk averse, that is, they will not wish to be self-insured, though demonstrably it is statistically correct to be so: in the long term the average insured cannot recover his premiums through claims.

'Analysis under uncertainty ' has the advantage of underlining the maximum risk that is associated with each particular outcome, i.e. the risk profile.
### 3.1.2 Risks / Uncertainties

The time-rate-of-roughening of the lining, which will result in a decrease in tunnel capacity with time, is the factor considered in the risk analysis. It is not possible to determine with certainty a single ultimate roughness value for the tunnel. Neither is it possible to determine with certainty the rate at which the tunnel will roughen with time. Uncertainty arises because the phenomenon of roughening is influenced by a number of variables, some of which are listed below:

- aggressiveness of water
- quality of the concrete
- quality of surface finish
- flow velocities
- presence of organisms which will give rise to sliming of the tunnel

In this analysis the time rate of roughening is assumed to be represented by the expression:

\[ k_t = \alpha t \]

where:
- \( k_t \) is the roughness in mm at time \( t \)
- \( t \) is in years after commissioning
- \( \alpha \) is a constant having the dimensions mm/year

The formula is a simplification of the Colebrook-White aging formula, \( k_t = k_0 + \alpha t \), where \( k_0 \), being small, is assumed to be zero.
3.2 Risk analysis approach to sizing

3.2.1 Probability distribution of $\alpha$ values

In order to accommodate uncertainties in the ultimate roughness and time rate of roughening a probabilistic distribution is assigned to the constant $\alpha$. Both the probable minimum (99,99% chance of exceedence) and the probable maximum (0,01% chance of exceedence) values for $\alpha$ are assigned on a judgemental basis substantiated by the following published data.

a) Relationship between pH of water and $\alpha$

Colebrook ("The Flow of Water in Unlined, Lined and Partly Lined Rock Tunnels" Proc. ICE, Paper No 6281, October, 1958) gives a tentative graphical relationship between pH and the maximum value of $\alpha$ such that

\[ \log \alpha = 2,7 - 0,8 \text{ pH} \quad (\alpha \text{ in inches/yr}) \]

which gives

\[ \log \alpha = 4,1 - 0,8 \text{ pH} \quad (\alpha \text{ in mm/yr}) \]

The following pH values and resulting roughness are judged to be limiting.

<table>
<thead>
<tr>
<th>pH</th>
<th>$\alpha_{k}$ mm/year</th>
<th>$\alpha_{n}$ mm (R=1,1m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,0</td>
<td>0,03</td>
<td>0,75</td>
</tr>
<tr>
<td>5,5</td>
<td>0,50</td>
<td>12,50</td>
</tr>
</tbody>
</table>

The maximum value of pH selected merely recognizes that the water will always be acidic.

The minimum value selected is that quoted by Colebrook (Derwent - Bamford main).

Eight samples of Lesotho water tested by the DWA (H.R.I.) show pH values between 6,9 and 6,2 with an average of 6,6.

b) Tunnel roughness at 25 years and 50 years

The figures for Manning's $n$ shown on the table in (a) are "n" estimated from the family of curves relating "k" and "R" (hydraulic radius) attached as Annex "A".

Viewed as possible but highly improbable limits that may be achieved these figures appear reasonable. Expressed as the roughness at 50 years the limits are:

Maximum (0,01% chance of exceedence) $n = 0,021$
Minimum (99,99% chance of exceedence)$n = 0,013$
Published data

Published data tend to be biased towards presenting "worst case" data. It is therefore not possible to obtain a balanced statistical analysis.

It is also probable that large increases in roughness are related to accretion (growth of organisms on tunnel walls) rather than to corrosion (attack of concrete surface). If the Delivery Tunnel exhibits roughening due to growth of organisms then cleaning during maintenance periods, which have been allowed for, is the indicated solution.

Published data have been summarised in Technical Memoranda H2 and are not repeated here. Examination of those data show that only one tunnel, the Appalachia conduit, displayed an α value greater than 0.5 mm/year. This arose because of growth of organisms.

On the basis of the above considerations limiting values of α = 0.03 and α = 0.50 have been adopted for the probabilistic analysis.

It has further been assumed that, between the limiting values the probability distribution of α values is a straight line on log probability paper (Figure 3-1).

The proposed probability distribution gives the following matrix of "n" values. The 98% and 2% chance of exceedence are shown as lowerbound and upperbound values being easily comprehended as the "one tunnel in fifty" probabilities.

<table>
<thead>
<tr>
<th>Lowerbound (98% chance of exceedence)</th>
<th>Median (2% chance of exceedence)</th>
<th>Upperbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06 mm/yr</td>
<td>0.127 mm/yr</td>
<td>0.275 mm/yr</td>
</tr>
<tr>
<td>5</td>
<td>0.0120</td>
<td>0.0125</td>
</tr>
<tr>
<td>10</td>
<td>0.0135</td>
<td>0.0145</td>
</tr>
<tr>
<td>25</td>
<td>0.0155</td>
<td>0.0175</td>
</tr>
<tr>
<td>50</td>
<td>0.0170</td>
<td>0.0190</td>
</tr>
</tbody>
</table>

Note: "k" - "n" conversions are correct to nearest 0.0005 in "n" value, are for R = 1.1 m and are according to Annex A.
LHWP Delivery Tunnel
Concrete Lining Ageing Predictions

Design Case:
k_\alpha at 25 years = 4mm
\alpha = 0,127 mm/yr

DT Head Losses Measurements: between 1998 – 2008:
\alpha = 0,013 mm/yr

Compare prediction by:
• Colebrook – White for pH = 6,6:
  \alpha = 0,066 mm/yr
• Levin (“Formulaire des Conduites Forcees Oleoducs et Conduites d’Aeration”, DUNOD, Paris, 1968)
  for mildly corrosive water
  \alpha = 0,025 mm/yr
ROOTE VAN DIE ORANGE-VISTONNEL
ROUTE OF THE ORANGE-FISH TUNNEL

Fig 1: Orange-Fish Tunnel route

Fig 2: 'Dry' tunnel reach, chainage 24,2 km, after final clean-up (May 1974)

Fig 3: 'Wet' tunnel reach, chainage 64,2 km, after final clean-up (May 1974)

DIE SIVIELE INGENIEUR in Suid-Afrika - Augustus 1991
Laser scan: PCC Lining Segments: LHTP D/T Outfall - 22/10/1999

\[ y = -0.004221x + 44.473909 \]

Distance to wall (mm)

Distance from start of scan (mm)

Laser scan: PCC Lining Segments: LHTP D/T Outfall - 22/10/1999 - detrended with sine wave of \( L = 374 \) mm and amplitude 0.76 mm superimposed

Distance to wall (mm)

Distance from start of scan (mm)
Looking at tunnel roughness

Research at Kárahnjúkar, Iceland, is providing fresh insight into tunnel wall roughness to estimate heads. Report by Patrick Reynolds

Kárahnjúkar Headrace Tunnel, Iceland

Predicted Hydraulic Roughnesses by Designers, using Pegram & Pennington methods after hundreds of Laser Scans of wall roughness of “as bored / as shotcreted” 7.2 / 7.6m diameter tunnel.

Above: Equivalent sand grain roughness calculated against rock type

MARCH 2008 Tunnels & Tunnelling International
<table>
<thead>
<tr>
<th>Rock Types (TBM bore)</th>
<th>‘Relative rugosity’ proportions $\Sigma(L_s+L_M+L_R)=L_{total}$</th>
<th>Laser-scan physical roughness profiles (±600 at 73 stns, 9 months), leading to Deduced ‘k’ values using Pegram &amp;Pennington theory</th>
<th>Predicted Friction Head Losses (total: ≈ 60m, i.e, ±10% of gross head available)</th>
<th>Remarks (Assume “Fully Rough Turbulent flow”) $n_{Mean,FRT} = \frac{k^{1/6}}{26}$ where $x_{max} = 26$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Siltstone</td>
<td>“Smooth”: 60%</td>
<td>3 mm</td>
<td>1.3m to 1.9m</td>
<td>$n_{Mean,FRT} = \frac{k^{1/6}}{26}$ = 0.00751/6/26</td>
</tr>
<tr>
<td>2 Sandstone</td>
<td>“Smooth”: 60%</td>
<td>5 mm</td>
<td>1.0m to 1.5m</td>
<td>$n_{Mean} \approx 0.017$</td>
</tr>
<tr>
<td>3 Conglomerate</td>
<td>“Shotcreted” 14% x 60% L_s** = 0.14x12 = 1.7 km</td>
<td>16.5 mm (“stand alone”)</td>
<td>2.0m to 2.5m</td>
<td>$n_{shot} \approx 0.019$</td>
</tr>
<tr>
<td>4 Pillow Breccia</td>
<td>“Medium”: 25%</td>
<td>9 mm</td>
<td>1.5m to 2.0m</td>
<td>$n_{Mean,FRT} = \frac{k^{1/6}}{26}$ = 0.01051/6/26</td>
</tr>
<tr>
<td>5 Scoria</td>
<td>“Shotcreted” 64% x 25% L_s** = 0.64x12 = 7.7 km</td>
<td>16.5 mm (“stand alone”)</td>
<td>2.5m to 3.0m</td>
<td>$n_{shot} \approx 0.019$</td>
</tr>
<tr>
<td>6 Scoria</td>
<td>“Shotcreted” 64% x 25% L_s** = 0.64x12 = 7.7 km</td>
<td>16.5 mm (“stand alone”)</td>
<td>2.5m to 3.0m</td>
<td>$n_{shot} \approx 0.019$</td>
</tr>
<tr>
<td>7 Pillow lava</td>
<td>“Rough”: 15%</td>
<td>14 mm</td>
<td>1.7m to 2.1m</td>
<td>$n_{Mean,FRT} = \frac{k^{1/6}}{26}$ = 0.0211/6/26</td>
</tr>
<tr>
<td>8 Cube-jointed Basalt</td>
<td>“Shotcreted” 9% x 15% L_s** = 0.09x12 = 1.1 km</td>
<td>16.5 mm (“stand alone”)</td>
<td>2.5m to 3.0m</td>
<td>$n_{shot} \approx 0.019$</td>
</tr>
</tbody>
</table>

**Assumption to meet the “25% shotcreted” statement – proportions not identified in article (or other assumptions – see context)**
Moody Diagram: Determines $\lambda$ factor from $D/k$ and Reynolds Number

Head Loss $h = \lambda \left( \frac{L}{D} \right) \left( \frac{v^2}{2g} \right)$ with $\frac{1}{\lambda} = (2 \log 3.7 \frac{D}{k})^2$; $n = \lambda^{\frac{1}{2}} D^{1/6}/11.15$
**Design Case:**

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Compare prediction by:
- Colebrook – White for pH = 6.6:
  - $\alpha = 0.066$ mm/yr
  - for mildly corrosive water
  - $\alpha = 0.025$ mm/yr

**LHWP Delivery Tunnel Concrete Lining Ageing Predictions**
UNLINED BORED TUNNELS

CONCLUSIONS & RECOMMENDATIONS

Clearly the most obvious issue that confronts a designer is that of predicting the “as built” hydraulic roughness of a bored tunnel — with that parameter “defined” then the next step — calculating the mean diameter of the tunnel is (at best) apparently quite straightforward, assuming that the flow regime will be nearly “fully rough turbulent” (that is, typically Re ≥ 10^6) and that one is in possession of the two other Chezy factors, Q_{DESIGN} and S_{DESIGN}; the latter of course being dependant on:

\[ h_{\text{net}} / L = [(\text{Intake WL} – \text{Outlet WL}) – \text{Secondary losses})] / L. \]

For example:

- Q_{DESIGN} = 100 cumecs
- S_{DESIGN} = 1: 1000
- n_{\text{NEW}} = 0.0155; hence k_{(\text{assume D = 6m})} = (0.0155 x 24)^6 = 0.003m = 3mm
- Hence D = \[\left(\sqrt{10.3 \times Q^*n}/\sqrt{S}\right)^{1/2.67} = \left[\left(\sqrt{10.3 \times 100 \times \sqrt{0.015}}\right)/(1/1000)\right]^{0.375} = 6.6m \text{ ID} \]

Check against Darcy Weisbach:

\[ \varepsilon = k/D = 3/6600 = 0.00045; \lambda = (2\log 3.7D/k)^{-2} = (7.5)^{-2} = 0.022 \]
\[ f = 124n^2 / D^{0.333} = 124 \times 0.0155^2 / 6.60^{0.333} = 0.016 \]
\[ R_e = VD/\nu = 2.92m/s \times 6.6/1.2x10^{-6} = 1.6x10^6; h_{\text{friction}} = fL/(V^2/2g) = (0.016*1/6.6)*(2.92^2/2g) = 0.00105 = 1:949: \text{OK!} \]

But is \( n = 0.0155 \) (k = 3 mm) “conservative” for “new tunnel” roughness?

- “Yes”, by reference to the D/T South derivations — where \( k_e \approx 3mm \) max (if secondary losses for expansions and contractions are not lowered beyond a credible value (that is, to Column “(3)” in Appendix 1, Table 1)

- But “no” - reference the Karahnjukar Tunnel data assuming that the forecast bored rock is of the “smooth” type then \( n_{\text{mean}} = 0.017 \) (\( k_{\text{mean}} = 7.5mm \)). But one must recall that the “P&P physical roughness” conversions used at Karahnjukar have yet to be verified via hydraulic flow trials and the “laser scan conversions” may be unduly conservative.

- However, the values for unlined bored tunnels called up under Section 2.10 above tend to vindicate a choice of \( n_{\text{mean}} = 0.018 \) – though it is not clear of course how such “conservative” values are arrived at – other than by application of the principle “if you are uncertain then take steps to reduce the risk of your design being proved inadequate” (“decision making under risk” – see below)

- And finally, the writer’s “personal” experience of a credibly derived roughness value for the primarily unlined Inanda-Wiggins bored tunnel is given by \( n_{\text{I-W (unlined)}} \approx 0.015 \) (k ≈ 2.5mm), a figure derived in respect of two contiguous tunnels during two sets of flow trials. However, this value is as usual highly dependant upon the “assigned” values for losses in the “other” portions of the tunnel (incl. secondary losses).

- However, when the issue of “aging” is addressed the use of \( k_{\text{bored sandstone}} = 7.5mm \) (k ≈ 0.0175) perhaps becomes more credible. But clearly the question of “aging” should be separately addressed - as should the issue of the type of rock being bored through)
SHOTCRETE LININGS TO BORED TUNNELS

What is apparent from the literature (and from the local “tunnel wall roughness laser scan surveys” of Messrs Pegram & Pennington) is that the application of shotcrete to stabilise bored-rock surfaces will not result in the reduction of the roughness of the surface (unless the surface of the bored rock is very “rough” – as was apparently the case for some 15% of the 36km long Kárahnjúkar Tunnel (in which instance all shotcrete was assessed at $k_{\text{shotcrete}} = 16.5$ mm – but only in terms of the conversion of (as yet inadequately hydraulically verified) “physical wall roughness profile” to “operational hydraulic roughness”.

The Pegram & Pennington laser scan ‘profiling’ of shotcreted bored tunnel walls in D/T South and Inanda Wiggins Emolweni & Clermont Tunnels resulted in (mathematically calculated) roughness values $k_{\text{shotcrete}}$ of the order of 3mm to 7mm – compared to the surrounding bored rock being deduced to have (from the Laser Scans) a deduced roughness of not greater than about 4 mm.

Hence one of the prime issues would appear to be forecasting the percentage of the unlined bored tunnel that will call for shotcrete lining. The case studies indicate “unlined bores” needing on average 25% of the overall tunnel length to be provided with shotcrete or concrete lining.

But it appears reasonable from the case studies and “miscellaneous established roughness values” called up, that unless the rock the tunnel is being bored through “undocumented” rock, use in the primary design analysis of an equivalent sand roughness value for shotcrete linings of $k_{s} = 7.5$ mm, ($n \approx 0.017$ for a “fully rough turbulent” flow regime) can be regarded as conservative (that is – greater than the probable median value) – if aligned with an equally conservative assessment of the proportion of shotcrete lining to the total length of the unlined bored tunnel in question.

The numerous other “uncertainty” issues (aging, secondary losses, construction quality, variable head availability, stability of demand etc, etc, - as mostly listed in the “SANCOT “Tunnel Roughness Concepts” diagram) of course have to be simultaneously addressed – possibly via a “probability/cost-risk-dilution decision tree”. The end result could be a decision to markedly reduce the degree of “hydraulic performance uncertainty” by going for a fully concrete lined tunnel.

And, if the “tenderer” comes up with a TBM that is bigger than the minimum design selection, then the necessity for precise estimation of the various tunnel hydraulic sizing parameters is immediately reduced in importance. But that is, of course, wishful thinking!

CONCLUSIONS & RECOMMENDATIONS
RISK & UNCERTAINTY IN DECISION MAKING

To conclude, herewith a formal reference to the philosophy that has been shown to permeate the whole question of how to size an “only partly lined” bored pressure tunnel:

“Decision making under certainty” – this represents typical engineering practice – “simple (or elaborate) number crunching”, in accordance with current design codes.

“Decision making under risk” (sometimes called “objective uncertainty” or “known unknowns”).

Under this scenario, the implicit assumption is made that for each possible alternative (or “possibility”) the probability of the occurrence is known – thus the employment of a “decision tree” to compute the cost of each “alternative” …( = probability x consequential cost).

“Decision making under uncertainty” (“subjective uncertainty” – or “unknown unknowns”, employing the enigmatic expression used recently by US politician Donald Rumsfeld).

In this case the outcome under each alternative is judged to be so uncertain as to preclude assigning a risk probability to it, hence the decision between alternatives will turn upon the “risk utility” of the owner – is he prepared to incur an additional present outlay to secure future “peace of mind”? – or, on the other hand, is he prepared to live with the possibility of a future penalty?. Most people are “risk averse” – that is, they will not wish to be self-insured – though it is statistically correct to be so (assuming of course that they are not “potentially dishonest claimants”).

“Analysis under uncertainty” has the advantage of underlining the possible maximum risk associated with each particular option – that is, the “random/ultimate risk profile”.

CONCLUSIONS & RECOMMENDATIONS
Thank You