Lecture 12  
Calibration of Canal Gates

I. Free-Flow Rectangular Gate Structures

- For a rectangular gate having a gate opening, \( G_o \), and a gate width, \( W \), the free-flow discharge equation can be obtained from Eq. 26 of the previous lecture, assuming that the dimensionless velocity head coefficient is equal to unity:

\[
Q_f = C_d G_o G_w \sqrt{2g(h_u - C_g G_o)}
\]  
(1)

where \( G_o \) is the vertical gate opening; \( G_w \) is the gate width; \( G_o G_w \) is the area, \( A \), of the gate opening; and, \( C_g \) is between 0.5 and 0.61

- The upstream flow depth, \( h_u \), can be measured anywhere upstream of the gate, including the upstream face of the gate
- The value of \( h_u \) will vary only a small amount depending on the upstream location chosen for measuring \( h_u \)
- Consequently, the value of the coefficient of discharge, \( C_d \), will also vary according to the location selected for measuring \( h_u \)

- One of the most difficult tasks in calibrating a gate structure is obtaining a highly accurate measurement of the gate opening, \( G_o \)
- For gates having a threaded rod that rises as the gate opening is increased, the gate opening is read from the top of the hand-wheel to the top of the rod with the gate closed, and when set to some opening, \( G_o \)
- This very likely represents a measurement of gate opening from where the gate is totally seated, rather than a measurement from the gate lip; therefore, the measured value of \( G_o \) from the thread rod will usually be greater than the true gate opening, unless special precautions are taken to calibrate the thread rod

- Also, when the gate lip is set at the same elevation as the gate sill, there will undoubtedly be some flow or leakage through the gate
- This implies that the datum for measuring the gate opening is below the gate sill
- In fact, there is often leakage from a gate even when it is totally seated because of inadequate maintenance
- An example problem will be used to illustrate the procedure for determining an appropriate zero datum for the gate opening

Sample Calibration

- Calibration data (listed in the table below) were collected for a rectangular gate structure
- The data reduction is listed in the next table, where the coefficient of discharge, \( C_d \), was calculated from Eq. 27
<table>
<thead>
<tr>
<th>Discharge, $Q_f$ (m$^3$/s)</th>
<th>Gate Opening, $G_o$ (m)</th>
<th>Upstream Benchmark Tape Measurement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0646</td>
<td>0.010</td>
<td>0.124</td>
</tr>
<tr>
<td>0.0708</td>
<td>0.020</td>
<td>1.264</td>
</tr>
<tr>
<td>0.0742</td>
<td>0.030</td>
<td>1.587</td>
</tr>
<tr>
<td>0.0755</td>
<td>0.040</td>
<td>1.720</td>
</tr>
<tr>
<td>0.0763</td>
<td>0.050</td>
<td>1.787</td>
</tr>
<tr>
<td>0.0767</td>
<td>0.060</td>
<td>1.825</td>
</tr>
</tbody>
</table>

Note: The discharge coefficient, $C_d$, was calculated using the following equation:

$$Q_f = C_d G_o g \sqrt{2g \left(h_u - \frac{G_o}{2}\right)}$$

- A rectangular coordinate plot of $C_d$ versus the gate opening, $G_o$, is shown in the figure below.
• Notice that the value of $C_d$ continues to decrease with larger gate openings.
• One way to determine if a constant value of $C_d$ can be derived is to rewrite Eq. 5 in the following format (Skogerboe and Merkley 1996):

$$Q_t = C_d \left( G_o + \Delta G_o \right) G_w \sqrt{2g \left( (h_u)_{\Delta G_o} - \frac{G_o + \Delta G_o}{2} \right)}$$  \hspace{1cm} (2)

where $\Delta G_o$ is a measure of the zero datum level below the gate sill, and

$$(h_u)_{\Delta G_o} = h_u + \Delta G_o$$  \hspace{1cm} (3)

• Assuming values of $\Delta G_o$ equal to 1 mm, 2 mm, 3 mm, etc., the computations for determining $C_d$ can be made from Eq. 3.
• The results for $\Delta G_o$ equal to 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm and 12 mm (gate seated) are listed in the table below.
• The best results are obtained for $\Delta G_o$ of 3 mm – the results are plotted in the figure below, which shows that $C_d$ varies from 0.582 to 0.593 with the average value of $C_d$ being 0.587.
• For this particular gate structure, the discharge normally varies between 200 and 300 lps, and the gate opening is normally operated between 40-60 mm, so that a constant value of $C_d = 0.587$ can be used when the zero datum for $G_o$ and $h_u$ is taken as 3 mm below the gate sill.
• Another alternative would be to use a constant value of $C_d = 0.575$ for $\Delta G_o = 4$ mm and $G_o$ greater than 30 mm.
<table>
<thead>
<tr>
<th>$Q_f$ (m³/s)</th>
<th>$G_0$ (m)</th>
<th>$h_u$ (m)</th>
<th>$\Delta G_0$ 0 mm</th>
<th>$\Delta G_0$ 1 mm</th>
<th>$\Delta G_0$ 2 mm</th>
<th>$\Delta G_0$ 3 mm</th>
<th>$\Delta G_0$ 4 mm</th>
<th>$\Delta G_0$ 5 mm</th>
<th>$\Delta G_0$ 6 mm</th>
<th>$\Delta G_0$ 7 mm</th>
<th>$\Delta G_0$ 8 mm</th>
<th>$\Delta G_0$ 12 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0646</td>
<td>0.010</td>
<td>1.836</td>
<td>0.756</td>
<td>0.638</td>
<td>0.630</td>
<td>0.582</td>
<td>0.540</td>
<td>0.504</td>
<td>0.472</td>
<td>0.445</td>
<td>0.420</td>
<td>0.344</td>
</tr>
<tr>
<td>0.0708</td>
<td>0.020</td>
<td>0.696</td>
<td>0.677</td>
<td>0.644</td>
<td>0.615</td>
<td>0.588</td>
<td>0.563</td>
<td>0.540</td>
<td>0.519</td>
<td>0.500</td>
<td>0.482</td>
<td>0.425</td>
</tr>
<tr>
<td>0.0742</td>
<td>0.030</td>
<td>0.375</td>
<td>0.654</td>
<td>0.632</td>
<td>0.612</td>
<td>0.593</td>
<td>0.575</td>
<td>0.558</td>
<td>0.542</td>
<td>0.527</td>
<td>0.513</td>
<td>0.471</td>
</tr>
<tr>
<td>0.0755</td>
<td>0.040</td>
<td>0.242</td>
<td>0.635</td>
<td>0.619</td>
<td>0.604</td>
<td>0.589</td>
<td>0.575</td>
<td>0.561</td>
<td>0.549</td>
<td>0.536</td>
<td>0.525</td>
<td>0.495</td>
</tr>
<tr>
<td>0.0763</td>
<td>0.050</td>
<td>0.175</td>
<td>0.625</td>
<td>0.611</td>
<td>0.599</td>
<td>0.586</td>
<td>0.575</td>
<td>0.563</td>
<td>0.552</td>
<td>0.542</td>
<td>0.531</td>
<td>0.514</td>
</tr>
<tr>
<td>0.0767</td>
<td>0.060</td>
<td>0.137</td>
<td>0.620</td>
<td>0.608</td>
<td>0.597</td>
<td>0.586</td>
<td>0.575</td>
<td>0.565</td>
<td>0.556</td>
<td>0.546</td>
<td>0.537</td>
<td>0.531</td>
</tr>
</tbody>
</table>

Notes: The last column with $G_0 = 12$ mm is for the gate totally closed. The discharge coefficient, $C_d$, was calculated from:

$$Q_f = C_d (G_0 + \Delta G_0) W \sqrt{2g\left(\frac{h_u}{\Delta G_0} - \frac{G_0 + \Delta G_0}{2}\right)}$$
II. Submerged-Flow Rectangular Gate Structures

- Assuming that the dimensionless velocity head coefficient in Eq. 27 is unity, the submerged-flow discharge equation for a rectangular gate having an opening, \( G_o \), and a width, \( W \), becomes:

\[
Q_s = C_d G_o G_w \sqrt{2g(h_u - h_d)}
\]

(4)

where \( G_o G_w \) is the area, \( A \), of the orifice.

- Field calibration data for a rectangular gate structure operating under submerged-flow conditions are listed in the table below.

- Note that for this type of slide gate, the gate opening can be measured both on the left side, \((G_o)_L\), and the right side, \((G_o)_R\), because the gate lip is not always horizontal.

- The calculations are shown in the second table below.

<table>
<thead>
<tr>
<th>Discharge, ( Q_s ) (m³/s)</th>
<th>Gate Opening</th>
<th>Benchmark Tape Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((G_o)_\text{left}) (m)</td>
<td>((G_o)_\text{right}) (m)</td>
</tr>
<tr>
<td>0.079</td>
<td>0.101</td>
<td>0.103</td>
</tr>
<tr>
<td>0.095</td>
<td>0.123</td>
<td>0.119</td>
</tr>
<tr>
<td>0.111</td>
<td>0.139</td>
<td>0.139</td>
</tr>
<tr>
<td>0.126</td>
<td>0.161</td>
<td>0.163</td>
</tr>
<tr>
<td>0.141</td>
<td>0.180</td>
<td>0.178</td>
</tr>
<tr>
<td>0.155</td>
<td>0.199</td>
<td>0.197</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( Q_s ) (m³/s)</th>
<th>( G_o ) (m)</th>
<th>( h_u ) (m)</th>
<th>( h_d ) (m)</th>
<th>( h_u - h_d ) (m)</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.079</td>
<td>0.102</td>
<td>0.823</td>
<td>0.643</td>
<td>0.180</td>
<td>0.676</td>
</tr>
<tr>
<td>0.095</td>
<td>0.121</td>
<td>0.819</td>
<td>0.633</td>
<td>0.187</td>
<td>0.674</td>
</tr>
<tr>
<td>0.111</td>
<td>0.139</td>
<td>0.816</td>
<td>0.620</td>
<td>0.196</td>
<td>0.668</td>
</tr>
<tr>
<td>0.126</td>
<td>0.162</td>
<td>0.813</td>
<td>0.626</td>
<td>0.187</td>
<td>0.666</td>
</tr>
<tr>
<td>0.141</td>
<td>0.179</td>
<td>0.810</td>
<td>0.615</td>
<td>0.195</td>
<td>0.660</td>
</tr>
<tr>
<td>0.155</td>
<td>0.198</td>
<td>0.808</td>
<td>0.615</td>
<td>0.193</td>
<td>0.659</td>
</tr>
</tbody>
</table>

- As in the case of the free-flow orifice calibration in the previous section, a trial-and-error approach can be used to determine a more precise zero datum for the gate opening.

- In this case, the submerged flow equation would be rewritten as:

\[
Q_s = C_d (G_o + \Delta G_o) G_w \sqrt{2g(h_u - h_d)}
\]

(5)
where $\Delta G_o$ is the vertical distance from the gate sill down to the zero datum level, as previously defined in Eq. 2

<table>
<thead>
<tr>
<th>$Q_s$ (m³/s)</th>
<th>$G_o$ (m)</th>
<th>$h_u - h_d$ (m)</th>
<th>$C_d$</th>
<th>$\Delta G_o = 4$ mm</th>
<th>$\Delta G_o = 6$ mm</th>
<th>$\Delta G_o = 8$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.079</td>
<td>0.102</td>
<td>0.1801</td>
<td>0.650</td>
<td>0.638</td>
<td>0.626</td>
<td></td>
</tr>
<tr>
<td>0.095</td>
<td>0.121</td>
<td>0.1865</td>
<td>0.651</td>
<td>0.641</td>
<td>0.631</td>
<td></td>
</tr>
<tr>
<td>0.111</td>
<td>0.139</td>
<td>0.1960</td>
<td>0.649</td>
<td>0.640</td>
<td>0.631</td>
<td></td>
</tr>
<tr>
<td>0.126</td>
<td>0.162</td>
<td>0.1869</td>
<td>0.650</td>
<td>0.642</td>
<td>0.635</td>
<td></td>
</tr>
<tr>
<td>0.141</td>
<td>0.179</td>
<td>0.1949</td>
<td>0.646</td>
<td>0.639</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>0.155</td>
<td>0.198</td>
<td>0.1931</td>
<td>0.646</td>
<td>0.640</td>
<td>0.634</td>
<td></td>
</tr>
</tbody>
</table>

Note: The discharge coefficient, $C_d$, was calculated from Eq. 32:

- As before, the criteria for determining $\Delta G_o$ is to obtain a nearly constant value of the discharge coefficient, $C_d$
- The above table has the example computational results for determining the discharge coefficient, $C_d$, according to adjusted gate openings, $G_o$, under submerged flow conditions

### III. Calibrating Medium- and Large-Size Gate Structures

- A different form of the submerged-flow rating equation has been used with excellent results on many different orifice-type structures in medium and large canals
- The differences in the equation involve consideration of the gate opening and the downstream depth as influential factors in the determination of the discharge coefficient
- The equation is as follows:

$$Q_s = C_s h_s G_w \sqrt{2g(h_u - h_d)}$$  \hspace{1cm} (6)

and,

$$C_s = \alpha \left( \frac{G_o}{h_s} \right)^\beta$$  \hspace{1cm} (7)

where $h_s$ is the downstream depth referenced to the bottom of the gate opening, $\alpha$ and $\beta$ are empirically-fitted parameters, and all other terms are as described previously
Note that $C_s$ is a dimensionless number.

- The value of the exponent, $\beta$, is usually very close to unity.
- In fact, for $\beta$ equal to unity the equation reverts to that of a constant value of $C_s$ equal to $\alpha$ (the $h_s$ term cancels).

- The next table shows some example field calibration data for a large canal gate operating under submerged-flow conditions.
- The solution to the example calibration is: $\alpha = 0.796$, and $\beta = 1.031$.
- This particular data set indicates an excellent fit to Eqs. 6 and 7, and it is typical of other large gate structures operating under submerged-flow conditions.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Discharge (m$^3$/s)</th>
<th>$G_o$ (m)</th>
<th>$\Delta h$ (m)</th>
<th>$h_s$ (m)</th>
<th>$G_o/h_s$</th>
<th>$C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.38</td>
<td>0.60</td>
<td>3.57</td>
<td>2.205</td>
<td>0.272</td>
<td>0.206</td>
</tr>
<tr>
<td>2</td>
<td>9.08</td>
<td>0.70</td>
<td>3.00</td>
<td>2.010</td>
<td>0.348</td>
<td>0.268</td>
</tr>
<tr>
<td>3</td>
<td>5.20</td>
<td>0.38</td>
<td>3.31</td>
<td>1.750</td>
<td>0.217</td>
<td>0.168</td>
</tr>
<tr>
<td>4</td>
<td>4.27</td>
<td>0.30</td>
<td>3.41</td>
<td>1.895</td>
<td>0.158</td>
<td>0.125</td>
</tr>
<tr>
<td>5</td>
<td>5.45</td>
<td>0.40</td>
<td>3.43</td>
<td>2.025</td>
<td>0.198</td>
<td>0.149</td>
</tr>
<tr>
<td>6</td>
<td>12.15</td>
<td>0.95</td>
<td>2.63</td>
<td>2.300</td>
<td>0.413</td>
<td>0.334</td>
</tr>
<tr>
<td>7</td>
<td>5.49</td>
<td>0.38</td>
<td>3.72</td>
<td>1.905</td>
<td>0.199</td>
<td>0.153</td>
</tr>
<tr>
<td>8</td>
<td>13.52</td>
<td>1.10</td>
<td>2.44</td>
<td>2.405</td>
<td>0.457</td>
<td>0.369</td>
</tr>
<tr>
<td>9</td>
<td>14.39</td>
<td>1.00</td>
<td>3.84</td>
<td>2.370</td>
<td>0.422</td>
<td>0.318</td>
</tr>
<tr>
<td>10</td>
<td>16.14</td>
<td>1.13</td>
<td>3.79</td>
<td>2.570</td>
<td>0.440</td>
<td>0.331</td>
</tr>
<tr>
<td>11</td>
<td>6.98</td>
<td>0.50</td>
<td>3.70</td>
<td>1.980</td>
<td>0.253</td>
<td>0.188</td>
</tr>
<tr>
<td>12</td>
<td>11.36</td>
<td>0.58</td>
<td>7.64</td>
<td>2.310</td>
<td>0.251</td>
<td>0.183</td>
</tr>
<tr>
<td>13</td>
<td>7.90</td>
<td>0.42</td>
<td>6.76</td>
<td>2.195</td>
<td>0.191</td>
<td>0.142</td>
</tr>
<tr>
<td>14</td>
<td>7.15</td>
<td>0.38</td>
<td>6.86</td>
<td>2.110</td>
<td>0.180</td>
<td>0.133</td>
</tr>
<tr>
<td>15</td>
<td>7.49</td>
<td>0.51</td>
<td>3.98</td>
<td>2.090</td>
<td>0.244</td>
<td>0.184</td>
</tr>
<tr>
<td>16</td>
<td>10.48</td>
<td>0.70</td>
<td>3.92</td>
<td>2.045</td>
<td>0.342</td>
<td>0.266</td>
</tr>
<tr>
<td>17</td>
<td>12.41</td>
<td>0.85</td>
<td>3.76</td>
<td>2.205</td>
<td>0.385</td>
<td>0.298</td>
</tr>
<tr>
<td>18</td>
<td>8.26</td>
<td>0.55</td>
<td>3.91</td>
<td>2.065</td>
<td>0.266</td>
<td>0.208</td>
</tr>
</tbody>
</table>

Note: the data are for two identical gates in parallel, both having the same opening for each data set, with a combined opening width of 2.20 m.
A similar equation can be used for free-flow through a large gate structure, with the upstream depth, \( h_u \), replacing the term \( h_s \), and with \( (h_u - G_o/2) \) replacing \( (h_u - h_d) \).

As previously mentioned, the free-flow equation can be calibrated using \( (h_u - 0.61G_o) \) instead of \( (h_u - G_o/2) \).

The following figure shows a graph of the 18 data points; the straight line is the regression results which gives \( \alpha \) and \( \beta \).

\[
\begin{align*}
\text{ln}(Cs) & \quad \text{vs.} \quad \text{ln}(Go/hs) \\
\alpha & = 0.796 \\
\beta & = 1.031
\end{align*}
\]

IV. Radial Gate Orifice-Flow Calibrations

- This structure type includes radial (or “Tainter”) gates as calibrated by the USBR (Buyalski 1983) for free and submerged orifice-flow conditions.
- The calibration of the gates follows the specifications in the USBR “REC-ERC-83-9” technical publication, which gives calibration equations for free and submerged orifice flow, and corrections for the type of gate lip seal.
- The calibration requires no field measurements other than gate dimensions, but you can add another coefficient to the equations for free flow and orifice flow in an attempt to accommodate calibration data, if available.
- Three gate lip seal designs (see figure below) are included in the calibrations:
1. Hard-rubber bar;
2. Music note; and,
3. Sharp edge

- The gate lip seal is the bottom of the gate leaf, which rests on the bottom of the channel when the gate is closed
- The discharge coefficients need no adjustment for the hard-rubber bar gate lip, which is the most common among USBR radial gate designs, but do have correction factors for the other two lip seal types
- These are given below for free and submerged orifice flow

- The gate radius divided by the pinion height should be within the range $1.2 \leq G_r/P \leq 1.7$
- The upstream water depth divided by the pinion height should be less than or equal to 1.6 ($h_u/P \leq 1.6$)
- If these and other limits are observed, the accuracy of the calculated flow rate from Buyalski’s equations should be within 1% of the true flow rate
**Free Orifice Flow** Free, or modular orifice flow is assumed to prevail when the downstream momentum function corresponding to $C_c G_o$, where $G_o$ is the vertical gate opening, is less than or equal to the momentum function value using the downstream depth. Under these conditions the rating equation is:

$$F_f = Q_f - C_{fcda} G_o G_w \sqrt{2g h_u} = 0$$ \hspace{1cm} (8)

where $C_{fcda}$ is the free-flow discharge coefficient; $G_o$ is the vertical gate opening (m or ft); $G_w$ is the width of the gate opening (m or ft); and $h_u$ is the upstream water depth (m or ft); $C_{fcda}$ is dimensionless.

- $C_{fcda}$ is determined according to a series of conic equations as defined by Buyalski (1983) from an analysis of over 2,000 data points.
- The equations are lengthy, but are easily applied in a computer program.

**Eccentricity**

$$AFE = \sqrt{0.00212 \left(1.0 + 31.2 \left(\frac{G_r}{P} - 1.6\right)^2\right)} + 0.901$$ \hspace{1cm} (9)

$$BFE = \sqrt{0.00212 \left(1.0 + 187.7 \left(\frac{G_r}{P} - 1.635\right)^2\right)} - 0.079$$ \hspace{1cm} (10)

$$FE = AFE - BFE \left(\frac{G_o}{P}\right)$$ \hspace{1cm} (11)

where $G_r$ is the gate radius (m or ft); and $P$ is the pinion height (m or ft).

**Directrix**

$$AFD = 0.788 - \sqrt{0.04 \left(1.0 + 89.2 \left(\frac{G_r}{P} - 1.619\right)^2\right)}$$ \hspace{1cm} (12)
\[ BFD = 0.0534 \left( \frac{G_r}{P} \right) + 0.0457 \] (13)

\[ FD = 0.472 - \sqrt{BFD \left( 1.0 - \left( \frac{G_o}{P} - AFD \right)^2 \right)} \] (14)

**Focal Distances**

\[ FX_1 = 1.94 \left( \frac{G_o}{P} \right) - 0.377 \quad \frac{G_o}{P} \leq 0.277 \] (15)

\[ FX_1 = 0.18 \left( \frac{G_o}{P} \right) + 0.111 \quad \frac{G_o}{P} > 0.277 \]

\[ FY_1 = 0.309 - 0.192 \left( \frac{G_o}{P} \right) \] (16)

and,

\[ FXV = \frac{h_u}{P} - FX_1 \] (17)

The correction on \( C_{\text{fcda}} \) for the “music note” gate lip seal design is:

\[ C_{\text{correct}} = 0.125 \left( \frac{G_o}{P} \right) + 0.91 \quad \text{(music note)} \] (18)

The correction on \( C_{\text{fcda}} \) for the “sharp edge” gate lip seal design is:

\[ C_{\text{correct}} = 0.11 \left( \frac{G_o}{P} \right) + 0.935 \quad \text{(sharp edge)} \] (19)

For the hard-rubber bar gate lip seal design, \( C_{\text{correct}} = 1.0 \). The preceding corrections on \( C_{\text{fcda}} \) for the “music note” and “sharp edge” gate lip seal designs were chosen from the linear options proposed by Buyalski (ibid).
Finally,

\[ C_{fcda} = C_{\text{correct}} \left( \sqrt{F E^2 (F D + F X V)^2 - F X V^2 + F Y_1} \right) \]  \hspace{1cm} (20)

**Submerged Orifice Flow**  The submerged orifice rating equation is:

\[ F_s = Q_s - C_{\text{scda}} G_o G_w \sqrt{2 g h_u} = 0 \]  \hspace{1cm} (21)

where \( C_{\text{scda}} \) is the submerged-flow discharge coefficient; and all other terms are as previously defined; both \( C_{\text{scda}} \) and \( C_{ds} \) are dimensionless

- Note that the square-root term does not include the downstream depth, \( h_d \), but it is included in the lengthy definition of \( C_{\text{scda}} \)
- As in the free-flow case, \( C_{\text{scda}} \) is determined according to a series of conic equations:

**Directrix**

\[ ADA = \left( 11.98 \left( \frac{G_r}{P} \right) - 26.7 \right)^{-1} \]  \hspace{1cm} (22)
\[ ADB = 0.62 - 0.276 \left( \frac{P}{G_r} \right) \]  
\hspace{4cm} (23)

\[ AD = \left( ADA \left( \frac{G_o}{P} \right) + ADB \right)^{-1} \]  
\hspace{4cm} (24)

\[ BDA = 0.025 \left( \frac{G_r}{P} \right) - 2.711 \]  
\hspace{4cm} (25)

\[ BDB = 0.071 - 0.033 \left( \frac{G_r}{P} \right) \]  
\hspace{4cm} (26)

\[ BD = BDA \left( \frac{G_o}{P} \right) + BDB \]  
\hspace{4cm} (27)

\[ DR = AD \left( \frac{h_d}{P} \right) + BD \]  
\hspace{4cm} (28)

\[ D = DR^{-1.429} \]  
\hspace{4cm} (29)

\textit{Eccentricity}

\[ AEA = 0.06 - 0.019 \left( \frac{G_r}{P} \right) \]  
\hspace{4cm} (30)

\[ AEB = 0.996 + 0.0052 \left( \frac{G_r}{P} \right) \]  
\hspace{4cm} (31)

\[ AE = \left( AEA \left( \frac{G_o}{P} \right) + AEB \right)^{-1} \]  
\hspace{4cm} (32)
\[
\text{BEK} = 0.32 - 0.293 \left( \frac{G_r}{P} \right) \quad (33)
\]

\[
\text{BE} = \text{BEK} + \sqrt{0.255 \left( 1.0 + 1.429 \left( \frac{G_o}{P} - 0.44 \right)^2 \right)} \quad (34)
\]

\[
\text{ER} = \text{AE}(D) + \text{BE} \quad (35)
\]

\[
E = \sqrt{\ln \left( \frac{ER}{D} \right)} \quad (36)
\]

**Vector \( V_1 \)**

\[
V_1 = \frac{E(D)}{1.0 + E} \quad (37)
\]

**Focal Distance**

\[
\text{AFA} = 0.038 - 0.158 \left( \frac{P}{G_r} \right) \quad (38)
\]

\[
\text{AFB} = 0.29 - 0.115 \left( \frac{G_r}{P} \right) \quad (39)
\]

\[
\text{AF} = \text{AFA} \left( \frac{G_o}{P} \right) + \text{AFB} \quad (40)
\]

\[
\text{BFA} = 0.0445 \left( \frac{P}{G_r} \right) - 0.321 \quad (41)
\]
\[ BFB = 0.155 - 0.092 \left( \frac{P}{G_r} \right) \]  (42)

\[ BF = BFA \left( \frac{P}{G_o} \right) + BFB \]  (43)

\[ FY = BF - \frac{AF(h_d)}{P} \]  (44)

- If \( FY \leq 0 \), then let \( FY = 0 \) and \( FX = 0 \). Otherwise, retain the calculated value of \( FY \) and,

\[ FX = \sqrt{V_1^2 + FY^2} - V_1 \quad \text{(for} \; FY > 0) \]  (45)

\[ VX = \frac{h_u}{P} - V_1 - \frac{h_d}{P} - FX \]  (46)

The correction on \( C_{scda} \) for the “music note” gate lip seal design is:

\[ C_{correct} = 0.39 \left( \frac{G_o}{P} \right) + 0.85 \quad \text{(music note)} \]  (47)

The correction on \( C_{scda} \) for the “sharp edge” gate lip seal design is:

\[ C_{correct} = 0.11 \left( \frac{G_o}{P} \right) + 0.9 \quad \text{(sharp edge)} \]  (48)

- For the hard-rubber bar gate lip seal design, \( C_{correct} = 1.0 \)
- The preceding corrections on \( C_{scda} \) for the “music note” and “sharp edge” gate lip seal designs were chosen from the linear options proposed by Buyalski (ibid)

Finally,
\[ C_{scda} = C_{correct} \left( \sqrt{E^2 (D + VX)^2 - VX^2 + FY} \right) \] (49)

References & Bibliography


