A discussion on the design of U-type sheet piles for cofferdams

Victor Li
Director
Victor Li & Associates Ltd
Sheetpiles commonly used for supporting deep excavations in Hong Kong
Common Types of Sheetpiles

• U-type sheetpiles
• Z-type sheetpile
• Hat-type sheetpiles
U-type sheet piles  
Z-type sheet piles  
Hat-type sheet piles

Lam (2010)
Basic Beam Theory

(a) Cross Section

(b) Bending Stress

(c) Shear Stress

Lam (2010)
• Implication:
  – Max. shear occurs at mid-point
  – U-type sheetpile may not act a fully composite section due to possible joint slippage
- Fully uncoupled U-type sheetpile (frictionless joint)

(a) Bending Stress
(b) Shear Stress

Lam (2010)
• Comparison for U-type sheetpile

<table>
<thead>
<tr>
<th>Sheetpile</th>
<th>Fully composite section</th>
<th>Smooth joint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zxx (cm³/m)</td>
<td>EI (cm³/m)</td>
</tr>
<tr>
<td>FSPII</td>
<td>875</td>
<td>17480</td>
</tr>
<tr>
<td>FSPIII</td>
<td>1340</td>
<td>33600</td>
</tr>
<tr>
<td>FPSIV</td>
<td>2270</td>
<td>77200</td>
</tr>
</tbody>
</table>
Method for Enhancing Shear Resistance of Interlock

- Technique
  - Crimping (in factory)
  - Welding (on site or in factory)
• Crimped/welded doubles

(source: ArcelorMittal brochure)
• Crimped/welded triples

– can be treated as fully composite section

Continuous wall

![Diagram of a continuous wall with a Triple U section]

Triple U
Continuous wall ($\beta_B = 100\%$)

Single U ($\beta_B = 30$ to $50\%$)

Double U ($\beta_B = 60$ to $80\%$)

Triple U ($\beta_B = 95$ to $100\%$)

(Kort, 2004)
• Problems with crimping/pre-welding
  – connected sheetpiles becomes wider
  – more difficult to handle and install
  – more vibration
  – shortage of experienced welders
Code Recommendations

• Reduction factor to moment capacity, $\beta_\text{B}$

$$M = \beta_\text{B} \ Z \ f_y$$

where

$Z = \text{section modulus for fully composite section}$
• Reduction factor to wall stiffness, $\beta_w$

$$l = \beta_D l_o$$

where $l_o = \text{second area of moment for fully composite section}$
BS EN 1993-5:2007 National Annex
Recommendations

<table>
<thead>
<tr>
<th>Type of U-pile unit</th>
<th>Number of structural support levels (see Note 1)</th>
<th>Reduction factors $\beta_B$ and $\beta_D$ referred to in 5.2.2 (2); 5.2.2 (9); 5.2.3 (2); 6.4 (3) (see Notes 2, 3, 4, and 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Highly unfavourable conditions (see Note 6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unfavourable conditions (see Note 7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Favourable conditions (see Note 8)</td>
</tr>
<tr>
<td></td>
<td>$\beta_B$</td>
<td>$\beta_D$</td>
</tr>
<tr>
<td>Singles or uncrimped doubles</td>
<td>0</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>&gt;1</td>
<td>0.65</td>
</tr>
<tr>
<td>Crimped or welded doubles</td>
<td>0</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>&gt;1</td>
<td>0.90</td>
</tr>
</tbody>
</table>
• Additional enhancement (limited to 1.0)

  – interlock not treated with sealant or lubricant:

    $\beta_B$ up 0.05
    $\beta_D$ up 0.05
– welding at wall top before excavation
<table>
<thead>
<tr>
<th>Reduction factor</th>
<th>Highly unfavourable conditions</th>
<th>Unfavourable conditions</th>
<th>Favourable conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_B$</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta_D$</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Depth of excavation (m)</td>
<td>min. weld length (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤2.5</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 to 3.5</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5 to 4.5</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5 to 5.5</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 to 6.5</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 6.5</td>
<td>500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Example 1: Uncrimped sheetpile
  
  – Favourable condition, > 1 layer of strut
  – no sealant or lubricant
  – no crimping or pre-welding

\[ \beta_B = 0.8 + 0.05 = 0.85 \]
\[ \beta_D = 0.55 + 0.05 = 0.6 \]
– If welding at top also carried out:

$$\beta_B = 0.8 + 0.05 + 0.2 = 1.05 \text{ (take 1.0)}$$

or $$\beta_B = 0.8 + 0.2 = 1.0 \text{ (??)}$$

$$\beta_D = 0.55 + 0.05 + 0.25 = 0.85$$

or $$\beta_D = 0.55 + 0.25 = 0.8 \text{ (??)}$$
Traditionally, 
$\beta_B = \beta_D = 1$ used for design for decades.
• Worked example 1: 6m deep excavation

![Diagram showing a 6m deep excavation with DGWL at +6.0, FILL with c=0kPa, \( \phi = 35^\circ \), \( \gamma = 19 \text{kN/m}^3 \), and E=8MPa. The excavation is supported by a sheetpile at -5.50.]
<table>
<thead>
<tr>
<th>Sheetpile</th>
<th>Unit weight (kg/m³)</th>
<th>$\beta_D$</th>
<th>Wall deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSPII</td>
<td>120</td>
<td>0.55 (no treatment)</td>
<td>66.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 (welding at top)</td>
<td>57.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (fully composite)</td>
<td>53.5</td>
</tr>
<tr>
<td>FSPIII</td>
<td>150</td>
<td>0.55 (no treatment)</td>
<td>52.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 (welding at top)</td>
<td>47.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (fully composite)</td>
<td>44.7</td>
</tr>
<tr>
<td>FSPIV</td>
<td>190</td>
<td>0.55 (no treatment)</td>
<td>42.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 (welding at top)</td>
<td>38.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (fully composite)</td>
<td>36.7</td>
</tr>
</tbody>
</table>

In all case, bending moment not critical.
• Worked example 2: 12m deep excavation
<table>
<thead>
<tr>
<th>Sheetpile</th>
<th>unit weight (kg/m³)</th>
<th>$\beta_D$</th>
<th>wall deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSPII</td>
<td>120</td>
<td>0.55 (no treatment)</td>
<td>185.5 (yielded)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8  (welding at top)</td>
<td>157.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1     (fully composite)</td>
<td>146.1</td>
</tr>
<tr>
<td>FSPIII</td>
<td>150</td>
<td>0.55 (no treatment)</td>
<td>143.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8  (welding at top)</td>
<td>132.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1     (fully composite)</td>
<td>127.1</td>
</tr>
<tr>
<td>FSPIV</td>
<td>190</td>
<td>0.55 (no treatment)</td>
<td>122.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8  (welding at top)</td>
<td>116.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1     (fully composite)</td>
<td>113</td>
</tr>
</tbody>
</table>
• Findings:

– Upgrade one sheetpile size to achieve similar wall deflection if no special treatment is intended
– Increase weight (waste?) by about 25%
Experimental Results:

- most experiments performed using unfilled joint with no applied pressure
- presence of earth pressure and soil infill in joints increases shear resistance of interlock
- Hence, reduction factor not realistic
Experiments by Mawer & Byfield (2010)
Bending Stress
• Comments

– Even Byfield’s experiment not realistic enough
– Sands in interlocks pulverized and jam-pack the interlock during driving, causing significant locked-in stress and frictional resistance
– Connections of struts/waling to sheetpile restrain sheetpile movement
–fusing of steel during driving
A Field Experiment
• Findings:
  – No noticeable relative movement of sheetpiles
  – Slippage not a problem
Final Remarks

• Deficiency of theoretical and experimental studies leads to conservative reduction factors
• Design based on fully composite sheetpiles used for decades in Hong Kong without much problem.
• Interlock slippage seldom observed in reality due to various enhancement factors

  – earth pressure and hence friction
  – sand filling and hence more friction

  $(\mu = 1.65 \text{ or } \delta = 59^\circ \text{ reported by Mawer & Byfield, 2010})$
- friction up to 80 kN/m reported
– horizontal and vertical restraint by waling, brackets and short stud
– jamming due to deviation from verticality
– restrain of vertical movement by long embedment depth
- Design controlled by settlement. Stability usually not an issue.
- Design for cofferdam is already very conservative in Hong Kong.
- Use of reduction lead to even more conservative design
- No reduction factor needed generally when U-type sheetpiles driven in sand to avoid wastage of natural resources
• If reduction factor is to be applied:

  – Current practice:

    $$\beta_B, \beta_D \leq 1, \quad \beta_B > \beta_D.$$
– Suggested practice:

\[ \beta_B \leq 1, \quad \beta_W \approx 1 \]

with contingency measure to weld interlocks when slippage observed during excavation
References:

