Seine Nord Europe Canal – Comparison of two lock concepts with water-saving basins and optimisation of chamber structure

PIANC Workshop
15-16th October 2009

Presentation of the project
Seine-Nord Europe
Central link of the European Seine-Scheldt Waterway

• Eliminate a major bottleneck on the European high-capacity waterway network

• Improve competitiveness of industry
  • through the reliability and the reduced logistics costs of inland water transport
  • by offering common access in Europe to 6 seaports of the northern range (60% of Europe’s exports/imports)

• Contribute to regional development in France and Europe, reinforcing the capacity of exchange in the corridor Le Havre-Paris-Amsterdam/Dunkirk

Seine-Nord Europe Canal
meeting challenges at the regional, national and European levels

• develop accessibility of freight into the heart of large conurbations

• embody sustainable development issues in transport policies
  – by achieving a better modal split of freight movements
  – by contributing to a reduction in greenhouse gases and in the consumption of non-renewable energy

• tap the waterway’s potential for water transfer and tourism
Main technical features of the project

The project consists of a canal 106 km long (class Vb) from Compiègne to Aubencheul-au-Bac comprising:

- 8 pounds connected by 7 locks (single chamber) with water-saving basins
- 2 water storage reservoirs
- 3 aqueducts
- 59 other structures
- 55 million cubic metres of earthworks
- 2450 ha of land occupied by the canal
- 4 multimodal platforms and 7 loading/unloading quays
- 5 boat harbours + moorings for passenger vessels

Longitudinal profile of the Seine-Nord Europe Canal
Optimised water management

Carefully controlled water supply
- maximum watertightness of the canal and recycling of lockages
- constitution of reserves (storage reservoirs)

Value added by water transfer
- transfer of 1 - 2 m$^3$/s from the Oise to guarantee water supply to the Lille conurbation (outside low-flow periods on the Oise)
Description of the locks

Operating principle of water-saving basins

Cross-section through the middle of the chamber
\( n_{WSB} = 5 \) basins

Drop height (subdivision into \( n_{WSB} + 2 \) "virtual water layers")

To water-saving basins

Plan view of chamber
Comparison of two lock concepts

Integrated water saving basins

Separate water saving basins

Comparison of a few key functions
Water inlet methods to fill the chamber

Lateral inlet at the base of the side walls
System of longitudinal ducts + openings

Vertical inlet
System with perforated double apron

Description:
Longitudinal ducts: min. section 20 m² (4.00 m x 5.00 m)
Openings (2.00 m x 0.25 m): 2 x 30 units at regular intervals (every 4.00 m)
Perfectly symmetrical arrangement of openings (jets face to face to dissipate energy)
The longitudinal ducts homogenise flow rates through the openings and contribute to energy dissipation

Lower chamber under the perforated apron:
height 3 m, width 12.50 m
Perforated apron: 1100 perforations, section 0.20 x 0.20 m
Water arrives from the WSB into the lower chamber
A regulating zone in the chamber enables the incoming cross flows to be converted into longitudinal flows.

Advantages
Reduced civil works: reduced foundation depth (~ 4.0 m)
Simpler structure
Flow tranquillisation in the chamber at least equal and even better
Downgraded mode with possible faulty gate

Drawbacks
Widening of the base of the side walls in order to house the water ducts → less advantageous with an optimised U-shaped chamber
Downgraded mode imposes complete non-use of a WSB level in the event of a faulty gate
Deepening of the structure
Cost of the perforated double apron
### Key functional components — Water-saving basins

<table>
<thead>
<tr>
<th></th>
<th>Integrated water-saving basins (WSB)</th>
<th>Separate water-saving basins</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height</strong></td>
<td>Basins one on top of the other: impossible to match the volumes of water of the WSBs with those of the lock chamber</td>
<td>Possibility of matching the WSB water volumes exactly with those of their corresponding water layer in the lock chamber</td>
</tr>
<tr>
<td></td>
<td>Of the 4.30 m height of the layer of water to be saved, a height of 1.50 m is lost through:</td>
<td>$H_{\text{water}} = \frac{H_{\text{drop}}}{(n_{\text{WSB}} + 2)} + 0.50 = 4.30 + 0.50$</td>
</tr>
<tr>
<td></td>
<td>• the slab thickness (0.80 m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• a layer of water remaining in the WSB (0.20 min)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• a layer of air (0.50 m) above the full basin</td>
<td></td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>~ length of chamber: 200 m</td>
<td>Free length &lt; chamber length (ease of water circulation): 184 m</td>
</tr>
<tr>
<td></td>
<td>Overflow pipes and and fall shafts at each end</td>
<td>Overflow by running off the canal slopes</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>Must make allowance for the space occupied inside the WSBs (water intake and bell-mouth of the upper basin)</td>
<td>Resulting width required: 15.20 m</td>
</tr>
</tbody>
</table>

### Comparative study of locks with separate or integrated water-saving basins

**Operation of two types of reinforced concrete structure**

<table>
<thead>
<tr>
<th></th>
<th>U-shaped chamber (separate WSB)</th>
<th>Lock with integrated WSBs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chamber cross-section</strong></td>
<td><img src="image1.png" alt="U-shaped chamber" /></td>
<td><img src="image2.png" alt="Lock with integrated WSBs" /></td>
</tr>
<tr>
<td><strong>Operation in pure planar deformation</strong></td>
<td></td>
<td>More complex operation:</td>
</tr>
<tr>
<td></td>
<td><img src="image3.png" alt="46.5 m" /></td>
<td>Rigidity of side walls + WSB in transverse plane competing with</td>
</tr>
<tr>
<td></td>
<td><img src="image4.png" alt="20 m" /></td>
<td>Rigidity of the WSBs in the horizontal plane</td>
</tr>
<tr>
<td></td>
<td>46.5 m</td>
<td>→ 3D modelling required with shell elements</td>
</tr>
<tr>
<td></td>
<td><img src="image5.png" alt="43.5 m" /></td>
<td>No contrast in rigidity between chamber heads</td>
</tr>
<tr>
<td></td>
<td>20 m</td>
<td>→ monolithic structure</td>
</tr>
</tbody>
</table>

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Lock with separate water saving basins – Optimisation of reference solution

Typical structure

• U – shaped or similar
• Structure with supported side walls, anchored by passive ties
• Structures with independent gravity side walls
### Distribution of concrete volumes (preliminary design reference solution)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lock chamber</td>
<td>Length about 200 m, width 12.50 m, Total height between 30 m and 46 m</td>
<td>43%</td>
</tr>
<tr>
<td>Headworks</td>
<td>Parallelepipedic gravity structures, Width ~ 37 m, length 20 m (u/s) and 40 m (d/s)</td>
<td>25%</td>
</tr>
<tr>
<td>Gate chamber</td>
<td>Housed under the water-saving basins, in the middle, Width 36 m, length between 50 m and 85 m</td>
<td>15%</td>
</tr>
<tr>
<td>Water-saving basins</td>
<td>3 to 5 basins per lock: 200 m x 16 m x 6.00 m</td>
<td>8%</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Linking water ducts, waiting quays</td>
<td>9%</td>
</tr>
</tbody>
</table>

→ Advantageous to optimise lock chamber

### Reference solution considered

Reference solution studied and selected
U-shaped structure with treated backfill (chalk - sand - silt)

[Diagram showing different lock chamber designs: Massive U-shaped chamber with chalk backfill, U-shaped chamber with treated chalk backfill, U-shaped chamber walls with Rollcrete gravity side walls.]

**Structural role of the backfill**

**Structural role of the reinforced concrete wall of the chamber**
Structural design of the lock chamber
Treated backfill: materials and method of use

• Hydraulic binder: cement or derivative (LSC binder)
• Binder content: maximum 5% – 6%
• Method of use: road-building technique, by layers:
  layer of levelled chalk, spreading of cement, mixing, compacting

Calculation parameters considered for predesign:
• Non-treated chalk fill: $f = 36^\circ$, $C = 0$, $E_0 = 20 – 40$ MPa
• Treated chalk fill: $f = 38^\circ$, $C = 150$ kPa, $E_0 = 200 – 400$ MPa
• Requires, however, a study of the non-treated chalk fill solution

Structural design of lock chamber — Reference solution considered

U-shaped chamber structure with treated lateral backfill

| Description | Change from self-stable structure to massive U-shape with the aim being to achieve a substantial reduction in lateral backfill thrust. Backfill reinforced with geogrids, geotextiles, rebars, welded mesh, tyres, gabions, etc. Solution with cement-treated in-situ chalk backfill |
| Advantages | • The reinforced concrete of the chamber remains structural but is has smaller cross-sections
  • Concrete inside the chamber is compressed
  • Excellent stiffness → little movement of head of side walls
  • Low-cost solution if backfill is made from treated chalk. |
| Drawbacks | • Few references of use in large massive structures (on the other hand, numerous references in road works)
  • Little information on fatigue behaviour so additional studies will be required |
| Conclusion | Highly advantageous concept with treated chalk |
Advantages:
• Productive use made of a material widely available on the project site
• High modulus of deformability:
  ➢ provides a good thrust block for the side walls (when chamber is full)
  ➢ limits settlement (foundation of water-saving basins)
• Cohesion of the material limiting pressure on the side walls
• Low additional cost compared to the gains on the reinforced concrete sections of the chamber
• References from road-building techniques

Drawbacks:
• Restrictions on placing methods (sensitive to frost and bad weather)
• Few references of applications to massive structures
• Interference thrust on side walls during compacting and before setting
• Little is known about behaviour under cyclic stress conditions, cracking.
Lock with integrated water saving basins – Optimisation of reference solution

Lock chamber with integrated WSB – Solution n°1

- Water introduced through a double perforated floor
- Gates at the level of the lower room
- Single well for each water intake and each gate
- Gate operating room below the lowest water saving basin
- Butterfly type gates (operating room not high enough for vertical lift gates)
- Wells for basin isolation stop logs housed in the side walls
- Headworks by-pass ducts situated at the lower level against the lock chamber, entering the chamber in the middle (and not at the end)
Lock chamber with integrated WSB – Solution n°2

- Water introduced at the base of the two side walls
- Gates situated at level n-1 in relation to water saving-basin n
- Certain wells, shared, situated between the basins and lock chamber

Optimised solution selection

Solution n°1 appears to be the most attractive:

- Simplest hydraulic system
- Lowest hydraulic inertia: potential gain in lockage time
- Best guarantee of lock chamber stillness
- Cost not a decisive factor
Comparison of the two optimised solutions

<table>
<thead>
<tr>
<th>U-shaped chamber (separate WSB)</th>
<th>Lock with integrated WSBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Advantages</td>
</tr>
<tr>
<td>• Numerous references for this system</td>
<td></td>
</tr>
<tr>
<td>• Lower construction costs (7%)</td>
<td></td>
</tr>
<tr>
<td>• Smaller volumes of concrete for average drop heights</td>
<td></td>
</tr>
<tr>
<td>• More massive lock chamber structure, less elaborate and hence faster to build</td>
<td></td>
</tr>
<tr>
<td>• Easier access to gates</td>
<td>• lock chamber stillness : slight advantage thanks to the possibility of introducing water from adjacent reaches in the middle of the lock chamber</td>
</tr>
<tr>
<td></td>
<td>• Simpler hydraulic circuit</td>
</tr>
<tr>
<td></td>
<td>• Less environmental impact</td>
</tr>
</tbody>
</table>
Optimisation of construction methods for the solution using locks with separated water saving basins

Seven locks in all

Lock 0 and lock 1, both in the Oise valley,
    specific in geotechnical terms, with the main differences being:
    • apron foundations just at the top of the chalk formation
    • presence of the water table at a high level
      ⇒ special construction methods required

Locks 2 – 3 – 4 – 5 and 6, built on the chalky plateau
    Very similar geotechnical configurations characterised by:
    • Cut relatively deeply into the chalk formation
    • Presence of a water table at a low level with respect to the structure
      ⇒ Similar construction methods
Lock 3: main features

- Chalk of odd mechanical properties (apart from the first three metres of weathered chalk)
- Low level water table

Solutions studied

- Solution 1: large foundation pit with sloping sides
  1a: with lateral backfill using untreated chalk
  1b: with lateral backfill using treated chalk
- Solution 2: one nailed wall level (13 m height)
  2a: with lateral backfill using untreated chalk
  2b: with lateral backfill using treated chalk
- Solution 3: two nailed wall levels (24 m height)
  3a: with lateral backfill using untreated chalk
  3b: with lateral backfill using treated chalk

Solution 1b
- Large excavated foundation pit
- Treated chalk lateral backfill

Solution 2b
- Nailed wall below el. 72.50 NGF
- Treated chalk lateral fill

Solution 3b
- Nailed wall below el. 84.00 NGF
- Treated chalk lateral fill
Construction method: Case of lock 3

Solution 1b: Large foundation pit with sloping sides and treated chalk lateral backfill
- High price
- Large footprint
- Very high treated backfill (more than 45 m)
  → sensitivity of the structure to this technique is too high

Solution 2b: Foundation pit with sloping sides for first 20 metres
Nailed wall (height 13 m)
Treated chalk lateral backfill (limited height of 28 m)

Advantages:
- Price
- Drainage gallery set at the optimum elevation
- Reasonable sensitivity with respect to the treated backfill
- Low height of nailed wall
- Smaller footprint

Solution 3b: Foundation pit with sloping sides for the first 8 metres
Nailed wall (height 25 m)
lateral backfill using treated chalk (limited height 16 m)

Advantages:
- Price
- Limited volume of treated backfill
- Smaller footprint

Drawbacks:
- Large height of nailed wall
- Drainage gallery set at a relatively high elevation

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Construction method: Case of lock 3

Construction costs per linear metre of lock chamber

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Earthworks</th>
<th>Transport &amp; dumping of surplus fill</th>
<th>Backfill</th>
<th>Concrete</th>
<th>Total</th>
<th>Cost criterion ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a: sloping foundation pit with chalk backfill</td>
<td>100</td>
<td>23</td>
<td>48</td>
<td>1170</td>
<td>1341</td>
<td>6</td>
</tr>
<tr>
<td>1b: sloping foundation pit with treated chalk backfill</td>
<td>90</td>
<td>22</td>
<td>225</td>
<td>860</td>
<td>1197</td>
<td>4</td>
</tr>
<tr>
<td>2a: nailed wall (h=13m) with chalk backfill</td>
<td>80</td>
<td>12</td>
<td>24</td>
<td>1118</td>
<td>1234</td>
<td>5</td>
</tr>
<tr>
<td>2b: nailed wall (h=13m) with treated chalk backfill</td>
<td>80</td>
<td>12</td>
<td>120</td>
<td>858</td>
<td>1070</td>
<td>1</td>
</tr>
<tr>
<td>3a: nailed wall (h=25m) with chalk backfill</td>
<td>92</td>
<td>9</td>
<td>24</td>
<td>1035</td>
<td>1160</td>
<td>3</td>
</tr>
<tr>
<td>3b: nailed wall (h=25m) with treated chalk backfill</td>
<td>92</td>
<td>9</td>
<td>110</td>
<td>879</td>
<td>1090</td>
<td>2</td>
</tr>
</tbody>
</table>

Optimised solution with treated backfill and nailed wall: 20% reduction in chamber cost

Summary of lock characteristics (single locks)

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Montmacq</td>
<td>Noyon</td>
<td>Campagne</td>
<td>Moislaimes</td>
<td>Havrincourt</td>
<td>Marquion / Bourlon</td>
<td>Oisy le Verger</td>
</tr>
<tr>
<td>Fall height (m)</td>
<td>6.41</td>
<td>19.57</td>
<td>15.50</td>
<td>30.00</td>
<td>22.50</td>
<td>20.11</td>
</tr>
<tr>
<td>Chamber length</td>
<td>195 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamber width</td>
<td>12.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mooring</td>
<td>5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total volume of concrete for all 7 locks</td>
<td>1 million m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total mass of steel reinforcement bars for all 7 locks</td>
<td>90 000 t</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total area of formwork for all 7 locks</td>
<td>830 000 m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel structures</td>
<td>5000 t</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 upstream gates, approx. 7 m x 7 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 downstream gates, approx. 14 m x 13.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 downstream gate, approx. 7 m x 13.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>126 water duct gates 3.5 m x 3.5 m</td>
<td></td>
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</tr>
</tbody>
</table>

7 pumping stations with a total of 21 pumps with unit capacity ranging from 400 to 1900 kW
Installed capacity from 1.8 to 6.9 MVA per lock with a total of 28 MVA
Overall annual electricity consumption of 50 GWh (2013) rising to 87 GWh (2025)
Hydraulic simulations

Physical model of the 30 m lock - 1:25 scale
Results obtained in normal operation

- Filling time: of the order of 13 min 30s
- Longitudinal slope in the locks chamber remains at 0.1%
- Wave with a maximum amplitude of 1.15 m is observed in the water saving basins
- Downstream lockage wave remains less than 0.27 m high
Doubling of the locks

Doubling of locks: subject for in-depth study

- Traffic forecasts: 14 Mt by 2020 rising to 26 Mt by 2050
- Saturation will be reached 10 to 20 years after bringing the canal on stream

Allowance must be made for potential restrictions (geotechnical, land occupied) to lock doubling and/or subsequent lock doubling must be anticipated:
- oversizing of side wall when the ground thrust cannot be brought to bear,
- temporary underpinning of the upstream pound during canal doubling construction works,
- risks linked to the hydraulic gradient and to ground water flow,
- electro-mechanical equipment deferred for the second lock chamber.
Thank you very much for your attention