Physical Design of Upper Harbor at Auvelais Lock, Belgium

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Abstract: In the Meuse catchment in Belgium, the Auvelais lock nowadays allows for ECMT class Va ships (2000 tons, 110 m x 11.40 m). However, the present upper guard wall, which separates the upstream harbor from the river flow, is not well suited for class Va vessels because it is 110 m-long and its extremity is curved. There are plans to modernize the lock. To ease and secure the navigation, the new configuration should respect six criterions: it should (i) increase the space at the harbor entrance; (ii) minimize the stream velocity in the lock axis; (iii) reduce the transverse currents; (iv) ensure a smooth velocity gradient distribution to minimize the forces and yawing moments exerted on the vessel at the harbor entrance; (v) reduce the flow contraction in the river channel to maintain the river flood discharge capacity; and (vi) remain inexpensive. A 1:50 physical model is used to analyse the velocity field in the upper harbor for several geometries and discharges. The present layout is compared to three solutions: (1) a 124 m-long straight solid wall; (2) a 124 m-long straight wall with 9 openings; and (3) a 124 m-long straight wall with 5 openings. The result reproducibility is satisfactorily checked. The velocity profiles show that solution (3) gives the best results according to the six criterions.

Keywords: Cross currents, ports, guard wall, approach harbor, lock, inland navigation.

1. Introduction

Upstream and downstream the inland navigation locks, an approach harbor allows the ships to adjust their speed and course to enter (or leave) the lock safely. A guard wall separates the harbor from the river flow and protects it from currents. Vessels can then manoeuvre properly at lower speed. Yet at harbor entrance, vessels should have sufficient speed to counteract the cross currents and align into (or leave) the harbor. The guard wall should thus be long enough. It is either a solid wall or a perforated wall. Appropriate ports, i.e. openings, in the guard wall reduce transverse currents and eddy development in the harbor entrance. Entering the upper harbor is the most critical case because it is more difficult for the vessels sailing with the flow to reduce their speed and control their course.

General considerations and some recommendations about the design of lock approach areas were summarized by PIANC (2015), based on several worldwide guidelines and literature.

Systematic investigations were performed by the U.S. Army Corps of Engineers for upper guard wall design (Basham 2004; Stockstill 2001; Stockstill et al. 2005), with harbor entrance width up to 33 % of the whole channel width. To ensure efficient and safer navigation conditions, a balance should be obtained to minimize outdraft (i.e. the flow that moves around the end of the guard wall towards the dam, which tends to move the head of the tow out of the alignment with the guard wall) and draw towards the guard wall (i.e. the flow in the harbor that moves towards and under the guard wall towards the dam). The investigations showed that the ratio \( R \) of the total ported area along the guard wall to the intercepted cross-sectional area of the approach channel is a major factor in the performance of the guard wall. As a general rule, these areas should be equivalent \( (R = 1) \) according to a review of USACE real-scale projects. Stockstill et al. (2005) specified the optimum ratios (between 0.9 and 1.9) for distinct wall types due to physical and numerical models. These rules are not applicable in European larger harbor areas.

One key factor in European guidelines is to limit the transverse velocities: the maximum ranges between 0.2 and 0.35 m/s (PIANC 2015). Case-by-case studies are usually recommended, especially if the lock approach is connected to a waterway with flow velocities of more than 0.5 m/s. In Belgium, on river Meuse, the approaches of the new class VIb locks at Ivoz-Ramet (Bousmar et al. 2010) and Ampsin-Neuville (Bousmar et al. 2014) were designed recently with a composite modeling method, combining field measurements, 1D and 2D depth-averaged numerical modeling, physical modelling, and real-time navigation simulations. The optimization of the upstream approach layout with the physical model showed that the velocity gradient barrier is mainly governed by the upstream flow field and not by the downstream conditions: modifying the openings distribution only switch the gradient barrier upstream or downstream. The design of the openings with a converging shape across the wall reduced the flow contraction in the river channel, due to a jet effect along the wall reducing eddy formation (Bousmar et al. 2010).
The Auvelais lock (136.30 m x 12.50 m) is located in the navigable river Sambre, in the Meuse catchment, between Charleroi and Namur cities, in Belgium. It was initially built in 1936 for vessels belonging to ECMT class II (600 tons, 50 m x 6.60 m) but nowadays allows for class Va ships (2000 tons, 110 m x 11.40 m). In the framework of the North Sea-Mediterranean corridor of the TransEuropean Network of Transport, the traffic of large vessels is even expected to increase. However, the present upper harbor is not well suited for 2000 ton vessels. The guard wall is indeed 110 m-long only, and its extremity is curved to the inside of the harbor. Moreover, the lock is located just downstream of a meander at the right bank (Fig. 1). Thus, the 110 m-long vessels have difficulties to align into the lock: when the bow enters the lock, the stern is running the risk of touching and damaging the guard wall extremity. The Walloon administration is planning to modernize this upper harbor, whose width is about 40% of the total cross-section of the River Sambre.

This paper presents the design of a new upper guard wall at Auvelais lock, including the choice of the number and size of ports. To ease the navigation, the new configuration should respect six criterions (Swartenbroekx and Libert 2016). It should:

i. increase the space at the harbor entrance (minimum 4 m between the vessel and the wall);
ii. minimize the stream velocity in the lock axis \((v_x < 1 \text{ m/s})\);
iii. reduce the transverse currents \((v_y < 0.30 \text{ m/s} \text{ according to Rijkwaterstaat (2011)})\);
iv. ensure a smooth velocity gradient distribution to minimize the forces and yawing moments acting on the vessel at the harbor entrance;
v. reduce the flow contraction in the river channel to maintain the river flood discharge capacity; and
vi. remain inexpensive.

![Figure 1. Aerial view of the river Sambre and the existing guard wall at Auvelais lock.](image)

2. Experimental Set-Up

The flow and in particular the velocity field in the upper harbor are analyzed for several geometries with the help of a scale model, built in the Hydraulic Research Laboratory of the Walloon administration. Due to space and discharge constraints, the chosen scale is 1:50 according to Froude similarities (Kobus 1980). By notation, the index \(p\) is related to prototype or field data while the index \(m\) corresponds to physical model values. The \(x\)-, \(y\)-, and \(z\)-axes are the streamwise, the transverse, and the upward vertical axis, respectively.

2.1. Flume Characteristics

The flume is \(L_m = 20.2\) m-long and \(b_m = 2.8\) m-wide. The upper part of the model stands for \(L_p \approx 400\) m-long reach of the river Sambre, including the downstream part of the bend showed in Fig. 1, with Auvelais mobile weir as
downstream condition (Fig. 2). The downstream part is used for another case study. A fixed bed was scaled according to the field bathymetry collected in October 2012. An erosion area is observed upstream of the mobile weir ($z_{b,\text{min},p} = 85.04$ m above the sea level) while deposition occurs in the lock channel ($z_{b,\text{mean},p} = 86.91$ m) and upstream of the weir channel ($z_{b,\text{max},p} = 89.76$ m).

The water supply is realized by the laboratory’s water recirculation pipe system. An upstream tank and an inlet section allow for a homogeneous inlet flow. The tailwater level can be regulated via a flap gate at the end of the flume. A high discharge $Q_p = 100$ m$^3$/s ($Q_m = 5.65$ l/s) is tested, for which navigation is still authorized and occurring about 12 days a year. The usual free surface level is then $z_{w,p} = 91.60$ m above the sea level and the water depth is about $h_{w,p} \approx 4.70$ m in the lock channel ($h_{w,m} \approx 9$ cm). The impact on the weir conveyance of a flood discharge $Q_p = 250$ m$^3$/s ($Q_m = 14.13$ l/s) is also checked, with a water level $z_{w,p} = 92.14$ m.

![Figure 2. Auvelais scale model.](image)

### 2.2. Configurations

The existing 110 m-long guard wall (Fig. 3) is compared to three solutions:

1. a 124 m-long straight solid guard wall (Fig. 4);
2. a 124 m-long straight guard wall with 9 openings (Fig. 5); and
3. a 124 m-long straight guard wall with 5 openings (Fig. 6).

As depicted in Fig. 3, the existing 110 m-long guard wall is straight in the downstream part and curved in the upstream part. The inflection point is located at 76.5 m from the upper lock head. The upstream part presents 11 openings of variable widths. The cumulated port width is 13.3 m. The ratio $R$ of the total ported area along the guard wall to the intercepted cross-sectional area of the approach channel (as defined by Stockstill et al. 2005) is $R_0 = 13.3 / 21 = 0.63$. A lateral distance of only 1.6 m is available between the guard wall upper extremity and the lock wall axis. A class Va vessel is sketched in green to understand the difficulty to properly enter the lock chamber without risk of collision with the guard wall.

The three proposed 124 m-long straight guard walls maintain 4.2 m everywhere between the guard wall and the lock wall axis (Fig. 4-6). More space is thus given in the lock channel (both length and width) and should ease the manoeuvre to enter the upper harbor and the lock. Regarding solutions (2) and (3), the ports (in black) are 3 m-wide and the angle at 45° with the wall axis, similarly to the ports of the existing wall. They are separated by a constant width to ease the in-situ structure design and building. The cumulated port widths are 27 m and 15 m, respectively. The ratio $R_2 = 27 / 23.8 = 1.13$ (in the range of the optimum deduced by Stockstill et al. (2005)) and $R_3 = 15 / 23.8 = 0.63$ (such that the ratio $R_3 = R_0$).
Figure 3. Existing 110 m-long guard wall with 11 openings.

Figure 4. 124 m-long solid guard wall.

Figure 5. 124 m-long guard wall with 9 openings.

Figure 6. 124 m-long guard wall with 5 openings.
2.3. Measurement Equipment

The discharge is measured by means of electromagnetic flow meters installed in the supply line, with an accuracy of 0.2%. The water level is measured in three fixed locations with ultrasonic gauges. The water depth $h_{w,m}$ ranges between 4 and 14 cm. The sensor accuracy is claimed to equal 0.3 mm.  

The velocity fields are measured with an electromagnetic probe Deltares PEMS-30, at a mid-depth $h_m = 4$ cm. The small water depth does not allow several measurements in the vertical profile. A trolley enables the ability to follow the same grid of measurement points during each test. The cross-sections are separated by $\Delta x_{m1} = 10$ cm near the upper guard wall and $\Delta x_{m2} = 40$ cm elsewhere. The measurements are recorded during 30 s at 20 Hz every $\Delta y_{m1} = 5$ cm in the cross-sections during the first tests and every $\Delta y_{m2} = 10$ cm when reproducibility is checked. The electromagnetic probe accuracy is about $\Delta v_m = 1$ cm/s.  

The data acquisition is handled by means of the software HydroCap 3, a home-made environment developed with Labview (Bousmar 2008).

3. Results and Discussion

In these paragraphs, the measurement reproducibility is first checked; then, the velocity field is analyzed for each geometry; and, finally, the longitudinal profiles of the velocity components are compared.

3.1. Reproducibility

Fig. 7 shows the velocity components ($v_x,p$ in red, $v_y,p$ in blue) measured along a same cross-section for a couple of runs (crosses for run 1, circles for run 2) realized in similar conditions (same discharge and same water level). The result reproducibility is satisfactorily checked. The gap between the results is indeed usually less than 5 cm/s at prototype scale, i.e. usually less than the expected accuracy for the electromagnetic probe used in a 1:50 physical model.

Figure 7. Velocity component profiles (prototype values) when $Q_p = 100$ m³/s at cross-section $x_p = 168210$ m. 124 m-long guard walls: (a) solid, (b) with 9 openings, (c) with 5 openings. Comparison between 2 runs in similar conditions: (+) run 1, (o) run 2.
3.2. Existing Guard Wall

The velocity field measured in the existing geometry when the discharge $Q_p = 100 \text{ m}^3/\text{s}$ is shown at prototype scale in Fig. 8. The measured model contour is given in red. The black arrow in the right-hand corner legend stands for a velocity vector $v_p = 1 \text{ m/s}$.

When approaching the upper harbor, the river flow is contracted and headed towards the left weir channel. The transverse velocities increase just upstream the guard wall and across the wall ports. Downstream of the ports, the flow is realigned in the weir channel while weaker velocities appear in the lock channel. A recirculation area is generated by the shearing forces due to the rapid flow forcing the head water area.

![Figure 8. Velocity field $v_p$ along the existing guard wall ($Q_p = 100 \text{ m}^3/\text{s}$).](image)

3.3. Long Straight Solid Guard Wall

The velocity field along the straight solid wall is depicted in Fig. 9. Given the lack of ports, the flow contraction towards the weir channel is stronger and more abrupt than in the existing case. The transverse velocity at the harbor entrance is then higher. Moreover, some velocity vector magnitude exceeds 1 m/s in the weir channel. Two recirculation areas are noticed. (1) There is an upward flow along the guard wall in the weir channel due to the flow detachment at the wall extremity. The flow reattaches to the wall after about 60 m. (2) There is a recirculation area with a slower speed on the whole width of the lock channel.

![Figure 9. Velocity field $v_p$ along the 124 m-long solid guard wall ($Q_p = 100 \text{ m}^3/\text{s}$).](image)

3.4. Long Straight Guard Wall with 9 Openings

The flow contraction towards the weir channel is more gradual and occurs more downstream through the 9 openings (Fig. 10) in comparison with the solid guard wall (Fig. 9). There is no recirculation. The velocity is higher but progressively decreasing in the lock reach.
3.5. Long Straight Guard Wall with 5 Openings

In the case of a 124 m-long guard wall with 5 ports ($Q_p = 100 \text{ m}^3/\text{s}$ in Fig. 11 and $Q_p = 250 \text{ m}^3/\text{s}$ in Fig. 12), the flow is contracted both upstream the guard wall and through the openings. The velocities in the lock channel are then weaker. When $Q_p = 250 \text{ m}^3/\text{s}$ (i.e. during high stage discharge periods), it is checked that the flow contraction in the weir channel is not worse than in the existing case. The existing river flood discharge capacity would be maintained in this new configuration.
3.6. Comparison

Three sections parallel to the lock wall are depicted in Fig. 13: a left-wall lock axis (dy_p = 4 m from the guard wall), a central lock axis (dy_p = 10 m), and a right-wall lock axis (dy_p = 16 m). The velocity profiles interpolated along these sections are given in Fig. 14-15 for Q_r = 100 m³/s. The x-axis gives the distance from the upstream lock head (the origin is a blue point in Fig. 3). Fig. 14 shows the velocity component v_x,p parallel to the guard wall, while Fig. 15 gives the velocity component v_y,p perpendicular to the guard wall. The existing geometry (blue) is superimposed to the 124 m-long guard wall, with solid wall (cyan), with 9 openings (magenta) and with 5 openings (red), for comparison. The left vertical black line delimitates the upper extremity of the long straight wall. The right black line indicates the downstream extremity of the ports.

For each case, the velocity magnitudes and the gradients are more critical in the longitudinal section that is the nearest to the guard wall (dy_p = 4 m). Whatever the considered longitudinal section in the lock, the longitudinal velocity (v_x,p, v_y,p) profiles show the impact of the number of ports in the guard wall.

When there is no port (cyan), high velocity maxima and high velocity gradients are shifted where the flow contraction occurs: upstream of the harbor entrance. Slow velocities (-0.1 m/s < v_x,p < 0.1 m/s) are then reached downstream in the harbor. The lack of opening (or not enough ports) induces (1) an abrupt flow contraction with high velocity maxima and gradients in the upstream reach, (2) a recirculation area in the lock channel, and (3) a flow detachment from the wall extremity in the weir channel. Consequently, this solution does not respect the design criterions iv and v stated in the Introduction. The high transverse currents and the eddy development in the harbor entrance make it difficult for the vessels to align into the upper harbor. Moreover, the reduction of the flow section in the weir channel diminishes the river flood discharge capacity.

The straight guard wall with 9 openings (magenta) brings about similar longitudinal velocities as the existing wall and slower transverse components in the lock channel. In comparison with the 124 m-long solid guard wall, the area with high velocity gradients is shifted along the ports, as if there was a shorter solid wall. The cumulated port width is indeed so large that no flow contraction occurs upstream of the harbor entrance. The area where the vessels can decelerate and manoeuvre properly at lower speed to enter the lock safely is thus shortened. However, contrary to the case of a solid wall, there is no flow detachment from the wall extremity due to the 45° ports and because the flow contraction is less abrupt in the weir channel (comparing Figs. 9-10).

The straight guard wall with 5 openings (red) induces a better velocity field, regarding the velocity maxima and gradients, both at the harbor entrance and in the upper harbor. The maxima v_x,p are < 0.3 m/s and v_y,p are < 0.15 m/s in the area from the upstream guard wall extremity to the lock head. The transverse currents have particularly decreased in the upper harbor in comparison with the existing wall and the solid wall. And contrary to the wall with 9 openings, the transverse velocity has not increased upstream of the harbor entrance. The velocity gradients are also less abrupt than in the other cases. The flow propagates more gradually toward the weir channel through a longer distance (both upstream the upper harbor and through the 5 ports). Because of the reduced port area in comparison with the 9 openings case, the discharge is lower through the ports. Both the outdraft and the draw towards the guard wall in the upper harbor are then minimized in comparison with the existing wall. Besides, the flow detachment from the wall in the weir channel is not too strong and does not diminish the flood discharge capacity.

Figure 13. Longitudinal sections in the lock channel.
Figure 14. Longitudinal profiles of the longitudinal velocity component $v_{x,p}$ when $Q_p = 100$ m$^3$/s (prototype value). (a) At $dY_p = 4$ m, (b) at $dY_p = 10$ m, (c) at $dY_p = 16$ m from the guard wall. Comparison between (blue) existing guard wall, (cyan) solid wall, (magenta) wall with 9 openings, (red) wall with 5 openings.
Figure 15. Longitudinal profiles of the transverse velocity component $v_{yp}$ when $Q_p = 100$ m³/s (prototype value).
(a) At $dy_p = 4$ m, (b) at $dy_p = 10$ m, (c) at $dy_p = 16$ m from the guard wall.
Comparison between (blue) existing guard wall, (cyan) solid wall, (magenta) wall with 9 openings, (red) wall with 5 openings.
4. Conclusions

The existing upper guard wall in Auvelais lock, Belgium, is not well suited for ECMT class Va vessels. To design the new guard wall, a 1:50 scale model was built and used to compare the velocity field measured in several geometries. The longitudinal velocity profiles show that the solution with a longer guard wall (124 m-long) and five 0.3 m-wide openings (i.e. about the same cumulated port width as in the existing case) gives the best results according to the six self-imposed criterions mentioned in the Introduction.

i. The space at the harbor entrance is > 4.2 m between the vessel and the wall.
ii. The longitudinal velocity in the lock axis \( v_{x,p} \) is < 0.30 m/s in the upper harbor when \( Q_p \leq 100 \) m³/s.
iii. The transverse currents \( v_{y,p} \) are clearly < 0.30 m/s just upstream and in the upper harbor when \( Q_p \leq 100 \) m³/s.
iv. Smooth velocity gradient distributions are ensured thanks to the progressive flow contraction upstream and in the upper harbor.
v. The existing river flood discharge capacity is maintained when \( Q_p \leq 250 \) m³/s.
vi. A standard port size limits the building cost of the new guard wall.

The measured results show the importance of the cumulated port width in the design of a guard wall: this width should be neither too short, nor too large, to allow for gradual flow propagation towards the weir channel. In the proposed layout with 5 openings, the transverse currents are minimized both at the harbor entrance and in the upper harbor so that the outdraft and the draw towards the guard wall (in the sense of Stockstill et al. (2005)) are minimized. The ratio \( R \) of the total ported area along the guard wall to the intercepted cross-sectional area of the approach channel is 0.63, both in the existing wall and in the proposed new wall. This value is less than the optimum range deduced by Stockstill et al. (2005), probably due to the fact that the Auvelais upper harbor is wide (about 40% of the total cross-section of the River Sambre) in comparison with US harbors.

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6. References


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