Belgian sea locks – proven solution for a safe navigation access to harbors

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The two nautical conditions that since ancient times have determined the location and growth of sea harbors are accessibility and safety. These conditions are to some extent contradictory, as accessibility does not always benefit from safety precautions; and a wide, free access is not necessarily the safest option. For this reason, combining these two conditions has always been a challenge to both designers and administrators of sea harbors.

The solutions in this field largely depend on local conditions, like:

– intensity and strategic importance of navigation,
– geology of the coast, space availability for construction,
– height of the tidal waves,
– height and frequency of storm surges,
– expected local sea level rise.

For the authorities and planners of harbors along the Baltic Sea coast, the most interesting are probably the experiences collected in the North Sea harbors over the last decades. Although the conditions of the Baltic Sea coast, like tides and storm surges, are generally milder, the expected sea level rise and extreme weather conditions – attributed to climatic changes – will likely demand new structural solutions. An additional reason is the growing throughput and economic value of the Baltic Sea ports. To put it simply – there are today more assets to care about in this region than a few decades ago; and the future will certainly increase both the number and the value of these assets. In this view, the structures and systems that provide safe access to the North Sea harbors may serve as examples to follow.

WHY PARTICULARLY BELGIAN LOCKS?

There are a number of structural solutions for a comfortable and safe navigation access to harbors. In the North Sea harbors of continental Europe, the tides are moderate or low with the difference between high and low tide (tidal range) rarely exceeding 4.0 m. This may seem much compared to the negligible Baltic

Sea tides but the tides on, for example, Atlantic coast of Europe are about twice as high. Under these conditions, the load cases that govern the dimensioning of port access facilities on the North Sea coast are usually the combination of:

- extreme storm surge level,
- corresponding wave loads (static and dynamic),
- astronomical tide (often the so-called “spring tide”),
- for quay walls and the like also the lowest tide levels.

These load components and their combinations have probabilistic character, which can also apply to water levels on the side of port basins. This usually results in a number of loading combinations that need to be considered. Obviously, these combinations will be different for structures like barriers, which are only operated for flood protection (in some cases also drought protection), and lock gates, which are primarily operated to facilitate navigation passage. The ways to determine the loading combinations in design of such structures are discussed in appropriate manuals, design codes and national regulations. Many examples from the latest engineering practice in Europe and America can be found in ref. [1].

Fig. 1 presents the location of the North Sea main navigation locks and storm surge barriers. The red circles (darker grey in black and white version) indicate sea locks with rolling (also called “sliding”) gates; the blue circles (lighter grey in black and white version) indicate the sea barriers and locks with gates of other types. Note that the sites with rolling gates are very frequent solutions to the accesses to port areas and inland navigation networks. Moreover, when the opening and closing frequencies are high – like in navigation locks – they are the most favored solution.

In view of navigation security, it is important that the sea locks are indeed accessible to ships, preferably 365 days a year and 24 hours a day. It is very normal that in new sea lock projects the so-called availability requirement exceeds 99%. For example, the contract for the Third Set of Locks in the Panama Canal required the availability of 99.6% of time on monthly basis [2]. Similar values can be found in construction contracts for the various new locks along the European North Sea coast, like the new Dutch IJmuiden Sea Lock [4] (99.0%). The Belgian construction contracts, like for the Kieldrecht Lock in Antwerp [3], did not – so far – include explicit availability percentage requirements, but the application of quality control tools, like the measure of continuous improvement, resulted in similar availabilities.

The arrangement that provides the highest confidence in meeting these requirements consists of double rolling gates at each lock head. These gates are most fit to retain the alternating loading from the seaside to inland and vice versa. They are also in all respects equivalent. In the most common scenario, one of the two gates is then active and operates to open and close the lock chamber, while the other gate is passive and remains in its recess as a stand-by device. When the operating gate has to undergo a maintenance service – either regular or unscheduled – the stand-by gate takes the operation over.

Maintenance of a lock gate is technically and logistically complex. Therefore, once initiated, it will usually be conducted on the entire system, including not only the gate itself but also its drive machinery, guides, rail tracks, load bearings and seals, and the control system. It will also cover the necessary inspections and tests. The most favored arrangement is then to have the entire gate as well as its drive fully redundant; and to perform all maintenance on the site. The aerial photo in Fig 2 shows two large sea locks in the harbor of Antwerp, the Berendrecht Lock and the Zandvliet Lock. One can see that the two locks contain double, fully redundant rolling gates and their drive mechanisms on both the harbor side (front in the photo) and the sea side (back in the photo). To facilitate the traffic across the locks, draw-bridges of bascule bridge type have been constructed at both ends of the lock chambers.

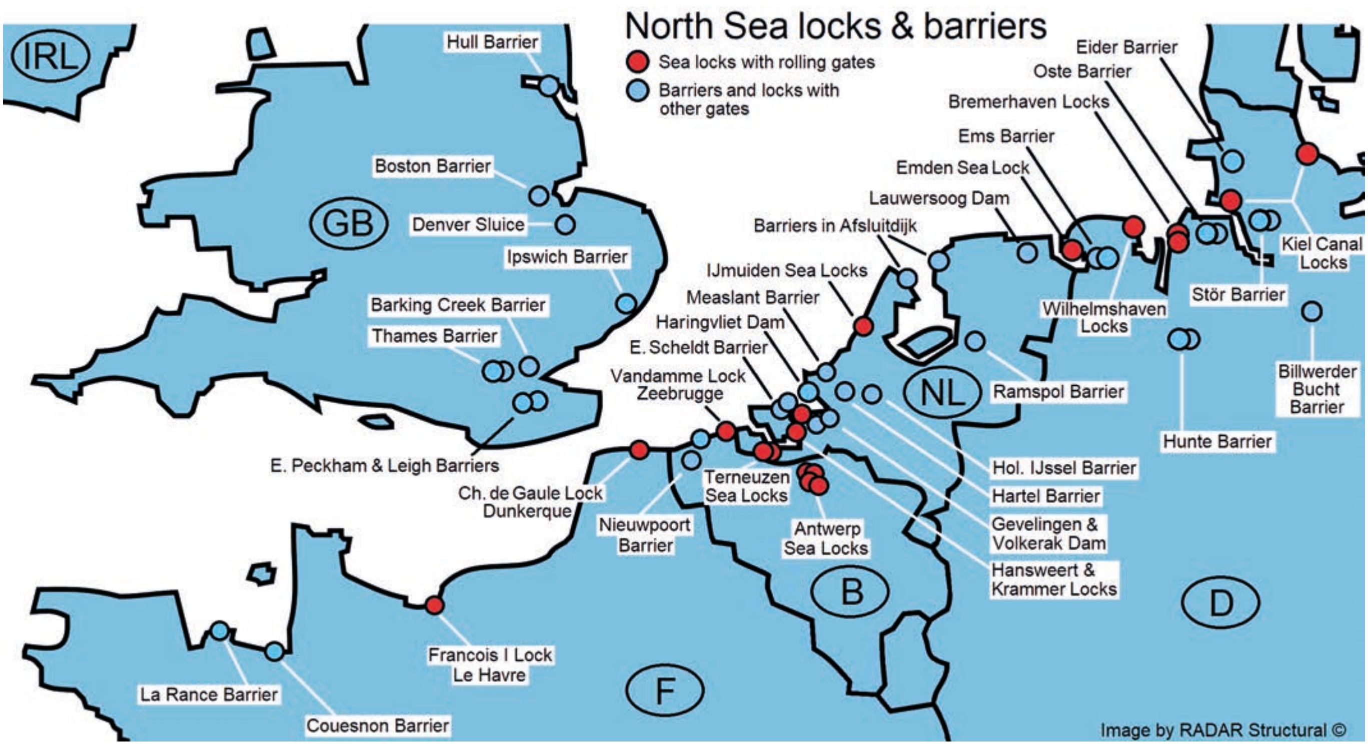
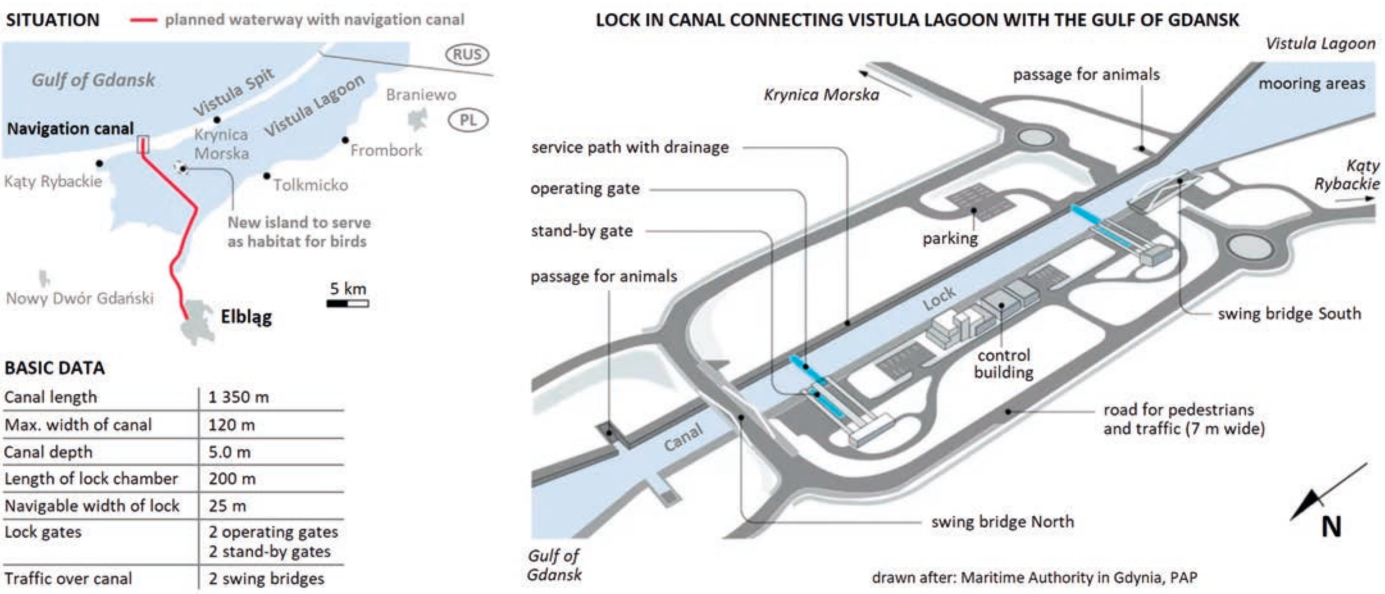


Fig. 1. Location of the main locks and storm surge barriers on North Sea coast

Fig. 2. Lock complex Berendrecht-Zandvliet in Antwerp, photo MOW Flanders

This is, in fact, the most common solution for sea locks with rolling gates. It is often called "Belgian-style locks", because all the large locks in Antwerp, the European second largest harbor are constructed in accordance with this arrangement. In addition, a number of French and Dutch sea locks and a lock in one other Belgian harbor (Zeebrugge) also closely follow this layout. For the readers in the countries around the Baltic Sea, this arrangement may be particularly interesting because it has also been chosen for the lock in the Vistula Spit Canal that is now under construction in the Gulf of Gdansk (Fig. 3). It will be the first navigation sea lock on the Polish Baltic Sea coast, making Poland enter the club of countries with controlled navigation conditions in harbors and maritime canals.



Canal length	1 350 m
Max. width of canal	120 m
Canal depth	5.0 m
Length of lock chamber	200 m
Navigable width of lock	25 m
Lock gates	2 operating gates 2 stand-by gates
Traffic over canal	2 swing bridges

Fig. 3. Lock in Vistula Spit Canal, under construction, general layout

Table 1. Most prominent Belgian-style sea locks and their gates

Lock name	Country	Chamber dimensions [m]			Gate weight [tons]	Thickness of gate [m]	Construction year
		Length	Width	Depth			
Panama Canal 3rd Set of Locks*	Panama	458	55	31.3	4250	10.64	2016
Kieldrecht Lock, Antwerp	Belgium	500	68	27.0	2000	10.98	2016
Berendrecht Lock, Antwerp	Belgium	500	68	23.0	1650	10.98	1989
Francois 1 Lock, Le Havre	France	401	67	22.5	3300	10.0	1971
Vandamme Lock, Zeebrugge	Belgium	500	57	24.3	1840	10.9	1985
Zandvliet Lock, Antwerp	Belgium	500	57	23.0	1570	10.98	1967
New Sea Lock Terneuzen (estimated)	Netherlands	427	55	21.2	1500	9.00	2022
Charles de Gaulle Lock, Dunkirk	France	365	50	23.0	1700	10.0	1970
Kallo Lock, Antwerp	Belgium	360	50	24.0	1470	10.98	1979
Boudewijn Lock, Antwerp	Belgium	300	45	19.0	870	8.58	1955
Western Lock Terneuzen	Netherlands	290	40	19.2	1000	7.00	1966
Sevilla Harbor Lock	Spain	300	40	20.0	900	6.00	2014
Van Cauwelaert Lock, Antwerp	Belgium	270	35	19.0	1300**	7.10	1928

*/ There are 6 gate sizes in this project [4]. These data apply to the Pacific gates PA2 and PA3.

**/ Including 350 tons of fixed ballast. Original gates replaced in 2009 by new rolling gates [6].

The good safety and reliability reputation of the Belgian-style sea locks has been confirmed by the choice of a similar system for a number of other sea locks in the world, including the Panama Canal Third Set of Locks, which also utilize double rolling gates at each lock head [4]. Table 1 presents the global data of some largest navigation locks of this system [1]. The focus is set on the gate structures, which are also of more interest in this article. The lengths and widths of lock chambers are navigable dimensions, while the depths are total dimensions from deck to bottom. Note that the navigable depths (ship draughts) are lower because chambers are usually constructed for extreme water levels during storm surges or floods.

Sea lock arrangements other than with double gates at each lock head are applied as well but are generally less favored, unless for special reasons. These can be space constraints, like in the new sea lock IJmuiden, the Netherlands [7], with one double- and one single-gated head. But these can also be strategic or other considerations, like in the Kiel Canal with double lock chambers rather than double gates in each lock head. In such cases, spare gates are usually provided and stored at close distance either in docks or ashore. Arrangements like these are, obviously, not the "Belgian-style locks".

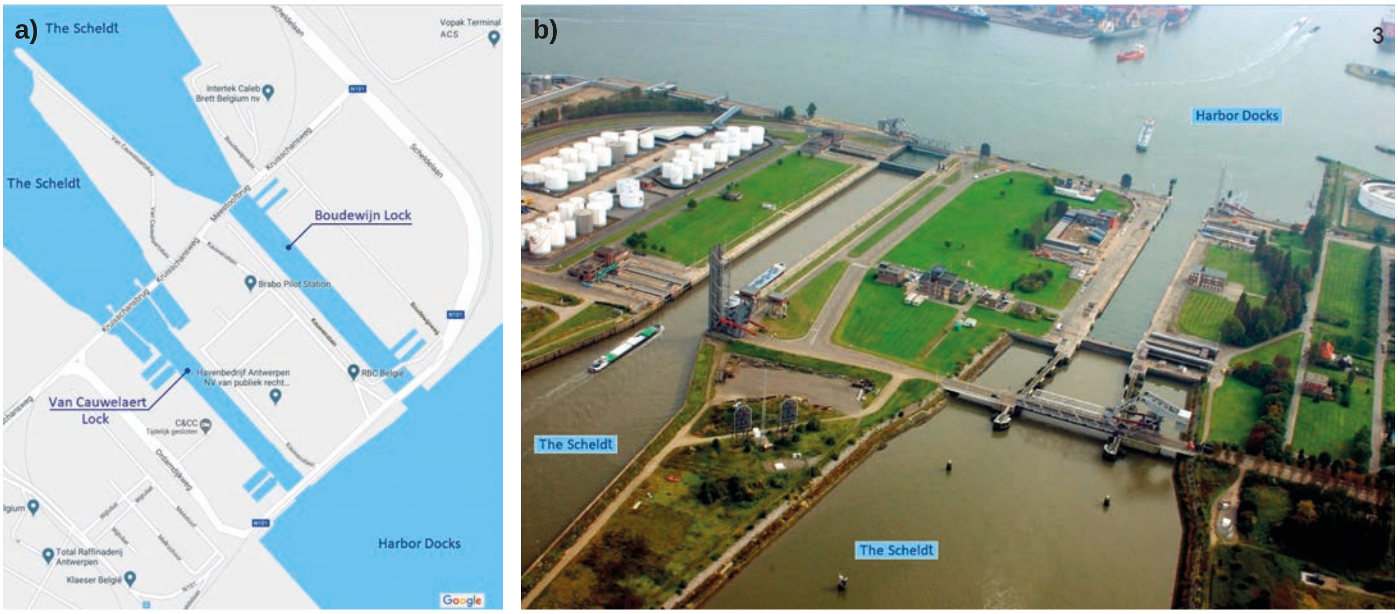


Fig. 4. Boudewijn and Van Cauwelaert Locks in Antwerp, layout (a) and aerial view (b), photo MOW Flanders

SYSTEMS AND COMPONENTS

In the terminology of systems engineering, a navigation lock is normally considered to be a system. This also applies to the Belgian-style sea locks. The main components of this system with – additionally – road traffic across the lock, are the following:

- Lock gates and their drives,
- Outer head,
- Inner head,
- Lock chamber,
- Filling and emptying devices,
- Mooring devices and fenders,
- Movable bridges at both heads.

It is not the purpose to discuss all these components here. Most of them can be observed in the photo of the Berendrecht and Zandvliet Locks in Fig. 2. These locks belong to the largest in the world. Fig. 4b shows an aerial photo of two smaller locks in the harbor of Antwerp, the Boudewijn and the Van Cauwelaert Locks. The dimensions of these locks remain larger than those of the future lock in the Vistula Spit Canal shown in Fig. 3, but the differences are not so striking any more. For a better comparison of spatial arrangements, a map with a network of roads around the Belgian locks is shown in Fig. 4a.

As one can notice, the very idea that gives these arrangements their high reliability is the same in Figs. 2, 3 and 4. Its main features are the following:

- Double lock gates and their drives:

  As discussed above, this enormously reduces the risk of lock operation failure. When one gate fails to operate or needs to be put out of service for inspection and/or maintenance, the other gate simply takes the operation over. In order to take full advantage of this idea, both gates must, obviously, be fully redundant. This means that the stand-by gate must operate in exactly the same manner and under the same performance parameters as the operating gate, since the two gates will be switching their functions. In engineering practice, this leads to two identical gates in a lock head. Locking of very large ships is sometimes allowed, even if only possible between the outer gates of a chamber.

- Two movable bridges with traffic regulation:

  In a general case, it is also possible to design the gate top decks for road traffic loads. Such arrangements can, e.g., be seen on several locks in the Netherlands and Germany. Also the lock gates in Belgium can often carry some traffic loads, usually from service vehicles. The solution with two movable bridges is more expensive, but also better. It not only offers a passage to more and heavier vehicles, but it also makes this passage independent from the gate operation – and by that more reliable. The bridges should, obviously, be placed outside the lock chamber and gate recesses.

- Optimal gate maintenance conditions:

  The entire separation of functions (locking the ships and passing the traffic) results in less constraints not only during operation but also for maintenance. For example, a major repair or maintenance on a gate will have no implications for the road traffic. As already mentioned, it will also have nearly no impact on the navigation. This reduces the time pressure and allows for optimal planning of maintenance activities on the lock gates, their drives, control systems etc. The same applies to movable bridges. A maintenance service on one bridge will restrict but not disable the road traffic; and will have no impact on the navigation.

An example of the latter is the planned replacement of the movable bridge superstructure and drive mechanism above the inner head (side of the harbor docks) of the Boudewijn Lock in Antwerp, shown left in Fig 4b. The existing bridges, constructed in the 1950s, are of the so-called Strauss type, named after Joseph Strauss, its inventor, who was also a chief engineer of the San Francisco Golden Gate Bridge. As shown in Fig. 4a, the lock inner head also carries a busy local road, which has resulted in fatigue of the bridge structure. This structure will soon be replaced by a bridge of a slightly different, so-called Scherzer type. The difference is that while the Strauss bridge moves

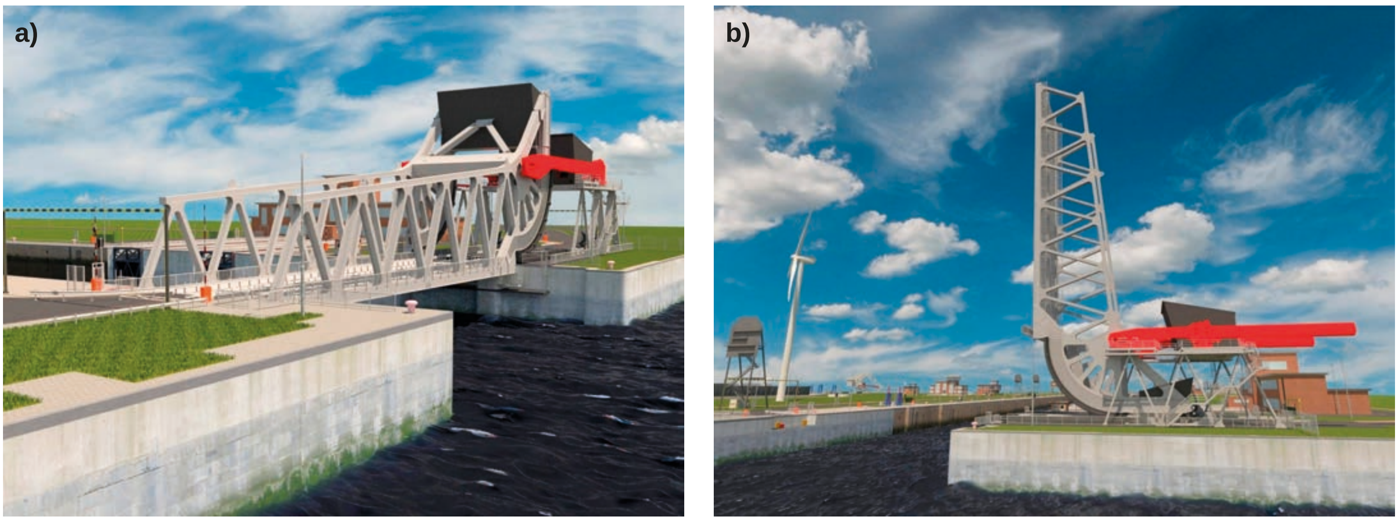


Fig. 5. New Boudewijn Bridge in Antwerp, closed (a) and open (b), courtesy of Matitieme Toegang, Port of Antwerp and Tracebel-Engie

around a fixed trunnion during opening, the Scherzer bridge additionally draws back by rolling on toothed racks. The model of the new Boudewijn Bridge is shown in Fig. 5 in a closed (a) and open (b) position.

These systems represent the technologies that are already over 100 years old, but they are still highly reliable, having their enthusiastic supporters among engineers. Moreover, one can even speak of some revival of mechanical drive systems in locks and bridges in recent decades, at the cost hydraulic drive systems. The discussion of this tendency falls, however, beyond the scope of this article. Important at this point is that also the very substantial refurbishments of system components, like the replacement of the Boudewijn Bridge for another type, do not affect the navigation through the Belgian-style sea locks.

MASSIVE STRUCTURES

Considering that locks are structures with large areas in plan view, engineers often succeed to construct them on shallow foundations. Piling or other deep foundation may be necessary on very weak soils, particularly under those massive components that transfer higher and more concentrated loads to the ground, like chamber walls, gate recesses and rail tracks.

If a lock chamber or a part of it is ever supposed to be set dry (for example to allow for easy replacement of rails), that part must be provided with watertight screens below the foundation level in order to prevent the seepage of water. Depending on local geological conditions and the expected differential water heads, seepage may also be an issue during normal operation. Typical means to prevent it are heavy sheet pile screens or diaphragm walls. An alternative is to construct a watertight lock chamber, in which case the bottom will also require piling but then against tensile loads from upward water pressure. Considering the widths of the Belgian sea locks, this is not an economical solution.

Chamber walls and the walls of gate recesses are conventionally stabilized against the varying horizontal water pressure in a way similar to quay walls. In the recent decades, grout anchors are very popular for this purpose. Examples from large locks and quays in the Netherlands and Germany have been presented in, respectively, [9] and [10]. This technology is widely practiced in Belgium as well. However, many old locks in that country rely on the stability of concrete monoliths alone, which in this case must have sufficiently wide foundations.

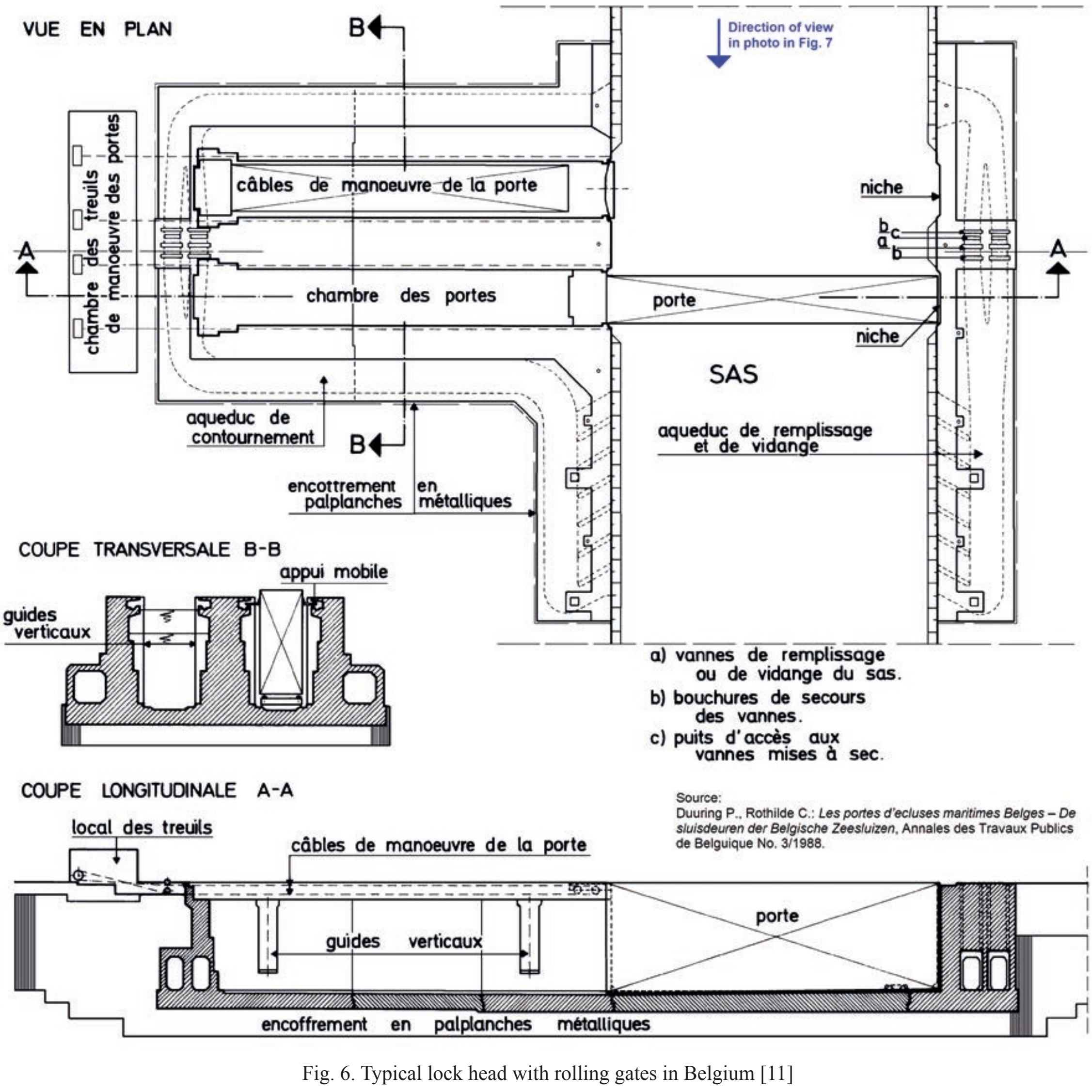


Fig. 6. Typical lock head with rolling gates in Belgium [11]

The latter is not difficult to obtain in the neighborhood of the lock heads. The chamber wall section can there be combined into one monolith with the section of longitudinal filling and emptying culvert. The width of the chamber wall support increases then tremendously, which usually makes additional piling or anchoring unnecessary. Many large navigation locks in Belgium utilize culvert systems that run a certain distance into the lock chamber to give a comfortable flow pattern during filling and emptying. The integration of culverts into one monolith with chamber walls is then an obvious choice.

An example of this arrangement is shown in Fig. 6 after [11]. This figure reflects the typical arrangement for a head of a large sea lock with double rolling gates, as shown earlier in the photos in Fig. 2 and 4. We have preserved the original French language in this drawing, partly in view of the ties between Gdańsk University of Technology and diverse French-language universities, strongly supported by professor Eugeniusz Dembicki. Engineers accustomed with hydraulic structures should not have much trouble understanding these notes. In addition, a view into the dewatered chamber of the Berendrecht Lock has been presented in a photo in Fig. 7. Observe the rail tracks of the gates and the in- and outlets of the filling and emptying culvert on the inner side of the chamber. This photo roughly corresponds with the direction of view as indicated by an arrow in Fig. 6.

The filling and emptying system consists in this case of the so-called "short culverts". As indicated in the drawing, these culverts run a certain distance into the lock chamber to spread the flows that might otherwise generate too high loads in ship hawsers and on mooring posts. This is, obviously of less importance outside the chamber, where no ships are moored. The in- and outlets on that side may, therefore, be more compact.

Other possible filling and emptying systems include, for example:

- Long culverts, reaching out far into the lock chambers. The in- and outlets are then often along the entire length of the chambers. This option is favoured at high-head locks, where the locking goes along with the replacement of large water volumes. This is seldom the case on the North Sea coast. In Belgium, it is only adopted in the Van Cauwelaert Lock.
- Long culverts with water-saving basins. Like above but with a capacity to store parts of the water volumes in so-called water saving basins. In Europe, practiced (so far) only in some inland high-head locks, but elsewhere also in sea locks. The most prominent example is the Panama Canal Third Set of Locks [5], [12].
- Filling and emptying openings with sluices in lock gates. This option fits the conditions with – to the contrary – low differential water heads, because gates give less opportunities to spread the filling flows than the chamber walls do. However, it is also practiced in large sea locks, like the new sea lock in IJmuiden, the Netherlands [1], [13].

The tidal ranges in Belgian harbors are slightly higher than those in the Netherlands, which explains why short culverts are usually the optimal choice. Nevertheless, filling and emptying openings in gates are also practiced. An example is the Pierre Vandamme Lock in Zeebrugge, with 5 circular openings in each rolling gate. The number of these openings will be extended to 9 during the coming refurbishment of the lock.

Fig. 7. View into chamber of the Berendrecht Lock [12]

Note that Fig. 6 also shows the outline of watertight screens (here of sheet piles) around the lock head area. In addition, it indicates the places where movement and expansion joints have been applied in the concrete structures. The latter should be understood as a safe arrangement in accordance with the views of 1980s; and – not to forget – for a large lock of about 60 m chamber width. The current views are generally in favor of larger distances between such joints in monolith concrete structures. This could, e.g., be seen in the chambers of the Panama Canal Third Set of Locks, as discussed in [14]. There are also first successful realizations of lock chambers without movement and expansion joints [15].

The latter is not exactly what the authors of this article would recommend, because movement and expansion joints are desired for more reasons than only thermal expansion. However, the current technology allows for more in this field than a few decades ago. Fig. 8 presents the details of joints between monolith concrete sections of the Naviduct in Enkhuizen (lock on an aqueduct) in the Netherlands, during construction. In this project, the largest horizontal dimensions of monolith sections were about 40 m. Note the aluminum-rubber seal that provides the watertightness of the joints between the concrete sections.

As can be seen in Figs. 6 and 8, concrete structures of navigation locks – particularly their heads – are voluminous, with thicknesses often in the range of a few meters. The casting of such structures presents a number of challenges, like the dissipation of hydration heat or the control of shrinkage. Some solutions to these issues have globally been discussed in ref. [9], with, as examples, two projects of massive chambers: Naviduct Enkhuizen in the Netherlands and Wulkan Nowy slipway in Szczecin shipyard, Poland. The provided data include, among others, the detailed concrete formulas, casting procedures and global results of laboratory tests. Readers are encouraged to review this data, because it shows important differences in comparison with concrete structures in other fields. Examples are the wide use of blast-furnace cement instead of Portland cement, applications of fly ash, plasticizers etc.

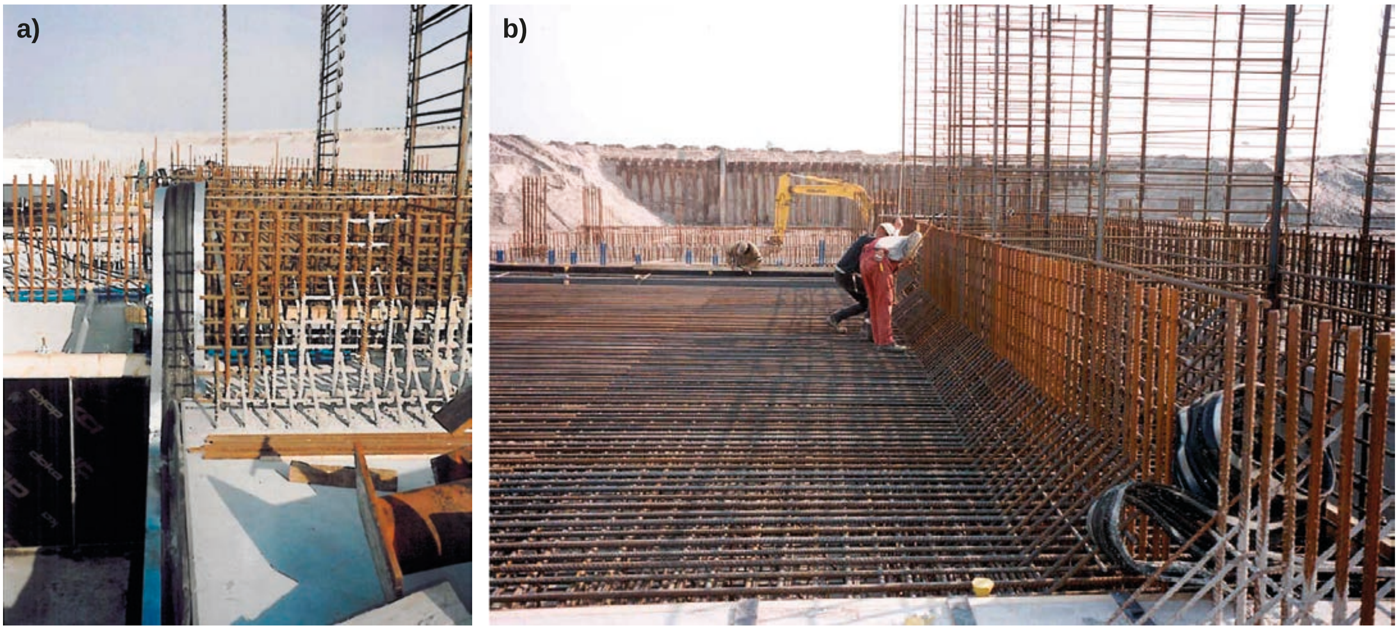


Fig. 8. Joints between monolith lock sections in Naviduct Enkhuizen, photos R. Daniel

ROLLING GATES

The gates of the Belgian-style sea locks are rolling gates of the so-called "wheelbarrow type". This name refers to the way in which these gates are supported during movement and when parked in the recess. In both positions, the gate passes its vertical loads (primarily self-weight but also buoyancy, possible ballast, variable deck loads, sediment and shell-fish deposition etc.) to two carriages, also called "wagons":

– lower carriage under the front bottom corner of the gate hull.
– upper carriage at the rear top corner of the gate hull.

This, naturally, requires two separate rail tracks to carry the gate: one on the bottom across the lock chamber, and one on the top of the gate recess walls. A critic might say that the two tracks make this system more complex, but nothing is less true. After all, the total length of the rail track is roughly the same as in the "competitive" system with both carriages under the gate, which is called "wagon type" by Belgian engineers. That the half of the track has been taken out of water and placed above is, in fact, a great advantage because it enables better inspections and maintenance. It also improves the stability of the gate under lateral loading by waves and residual head during opening and closing movements, because the gate center of gravity is then close to the diagonal tilting line that connects the supports to the two carriages.

Although the wheelbarrow gate is widely associated with the Belgian-style sea locks, it is not a Belgian invention. The first large sea lock that employed the gates of this type was the Bremerhaven North Lock, constructed in the years 1927-1931. The rolling gate designer was dr. Arnold Agatz, one of the most prominent German engineers of that time. The book about hydraulic gates [1] briefly discusses the backgrounds of this project; and provides the details of the Bremerhaven North Lock and its rolling gates.

While German engineers invented the wheelbarrow gate, their Belgian colleagues certainly brought this concept to perfection. The drawings in Figs. 9 and 10 present the side views of two lock gates of this system in the harbor of Antwerp, the Van Cauwelaert Lock gate and the Kieldrecht Lock gate. These two gates are deliberately chosen to represent, respectively, the smallest and the largest rolling gate from Table 1 earlier in this article. More drawings, photos and discussion of these structures can be found in [1].

Rolling gate structures consist, generally, of skin plates, a horizontal box-shaped chamber for buoyancy and ballast, and a system of horizontal and vertical frames. A skin plate is usually designed as an orthotropic plate that in some views resembles the orthotropic decks in steel bridges. For inland navigation locks, without inversion of water level difference, small rolling gates with a single skin plate may be sufficient. However, the larger gates – certainly in all Belgian-style locks that retain differential water heads in two directions – will have such plates at both sides. In this case, it is normally the downstream-side plate that receives the pressure of differential water head and passes it to the framing. An exception is the plate that makes part of the buoyancy chambers, where the loading conditions vary depending on whether the chambers are empty or full. As high water in the European North Sea harbors may appear at any of the two sides, both skin plates must be capable of carrying it; and are provided with horizontal and vertical bearings and seals.

The latter can be observed in the typical cross-section of a Belgian rolling gate, shown in Fig. 11 after ref. [11] and [1]. This cross-section refers to the gate of the Boudewijn Lock, shown in the aerial photo in Fig. 4. The gate was constructed in the 1950s, when the prices of steel were relatively high, resulting in the choice for thin skin plates (here 10 mm) often in the so-called "buckled plate" form. This form better utilizes the membrane effect while responding to hydraulic pressure. Similar buckled plates can still be seen in some decks of steel bridges of that time, but today they are considered outdated. Besides

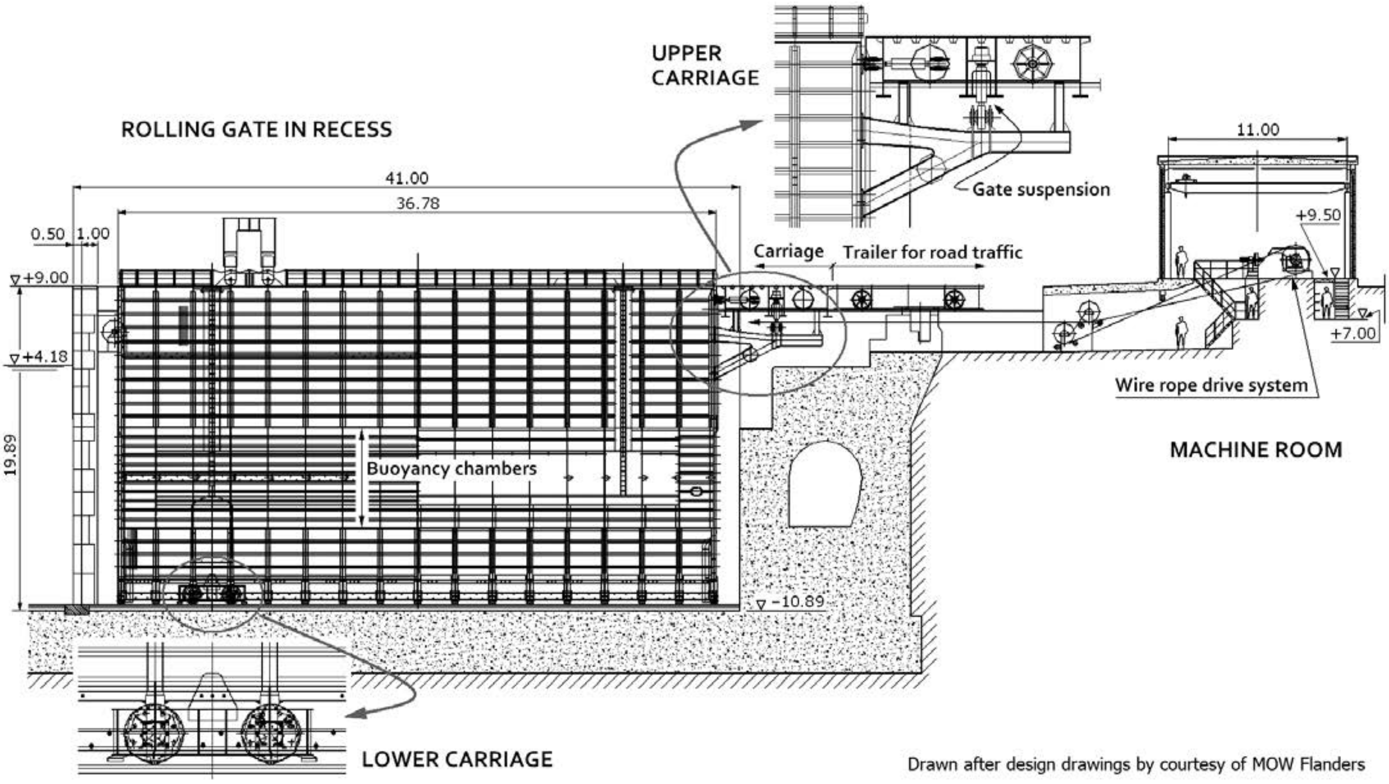


Fig. 9. Rolling gate and its drives in Van Cauwelaert Lock, Antwerp [1]

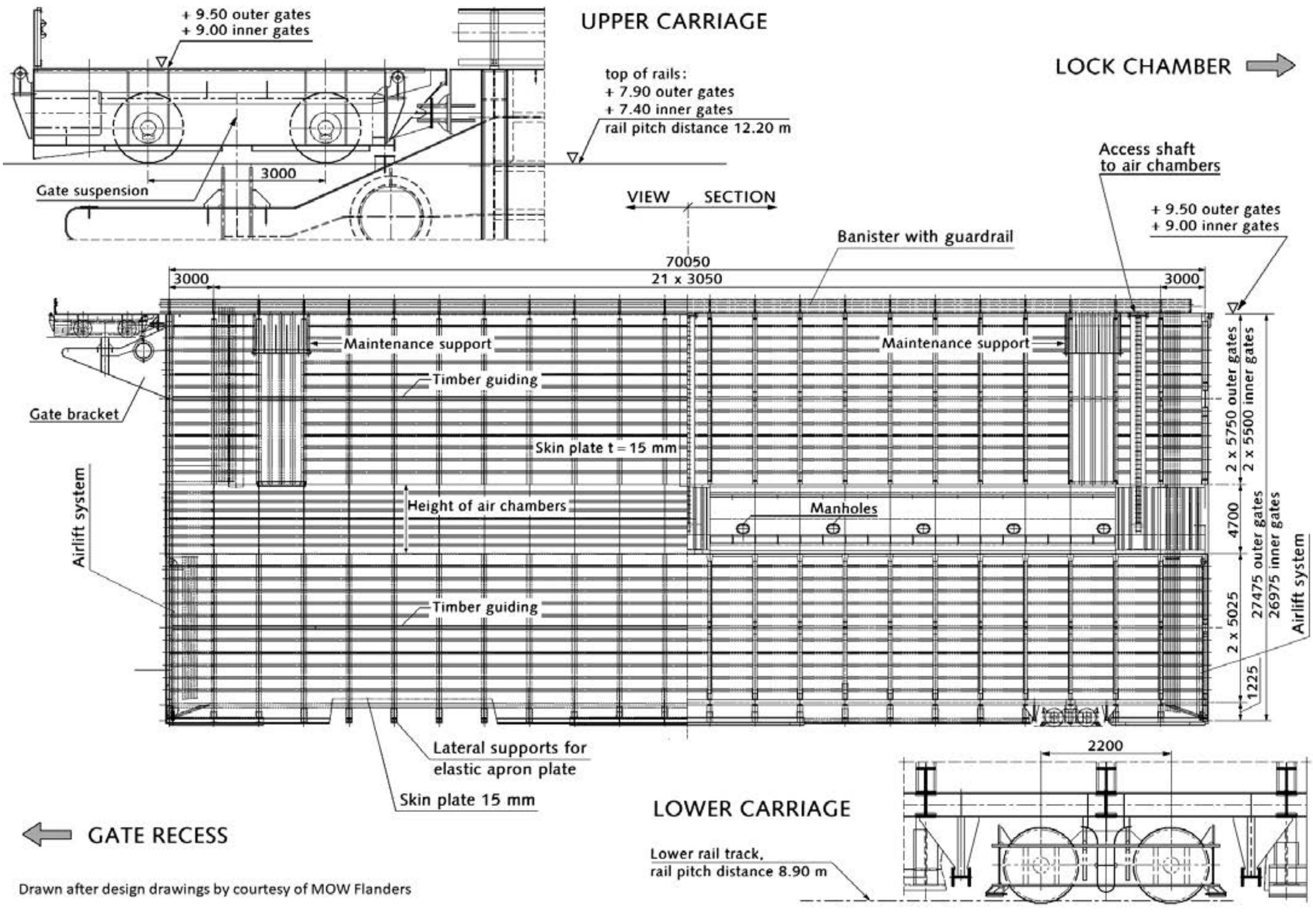


Fig. 10. Rolling gate and its carriages in Kieldrecht Lock, Antwerp [1]

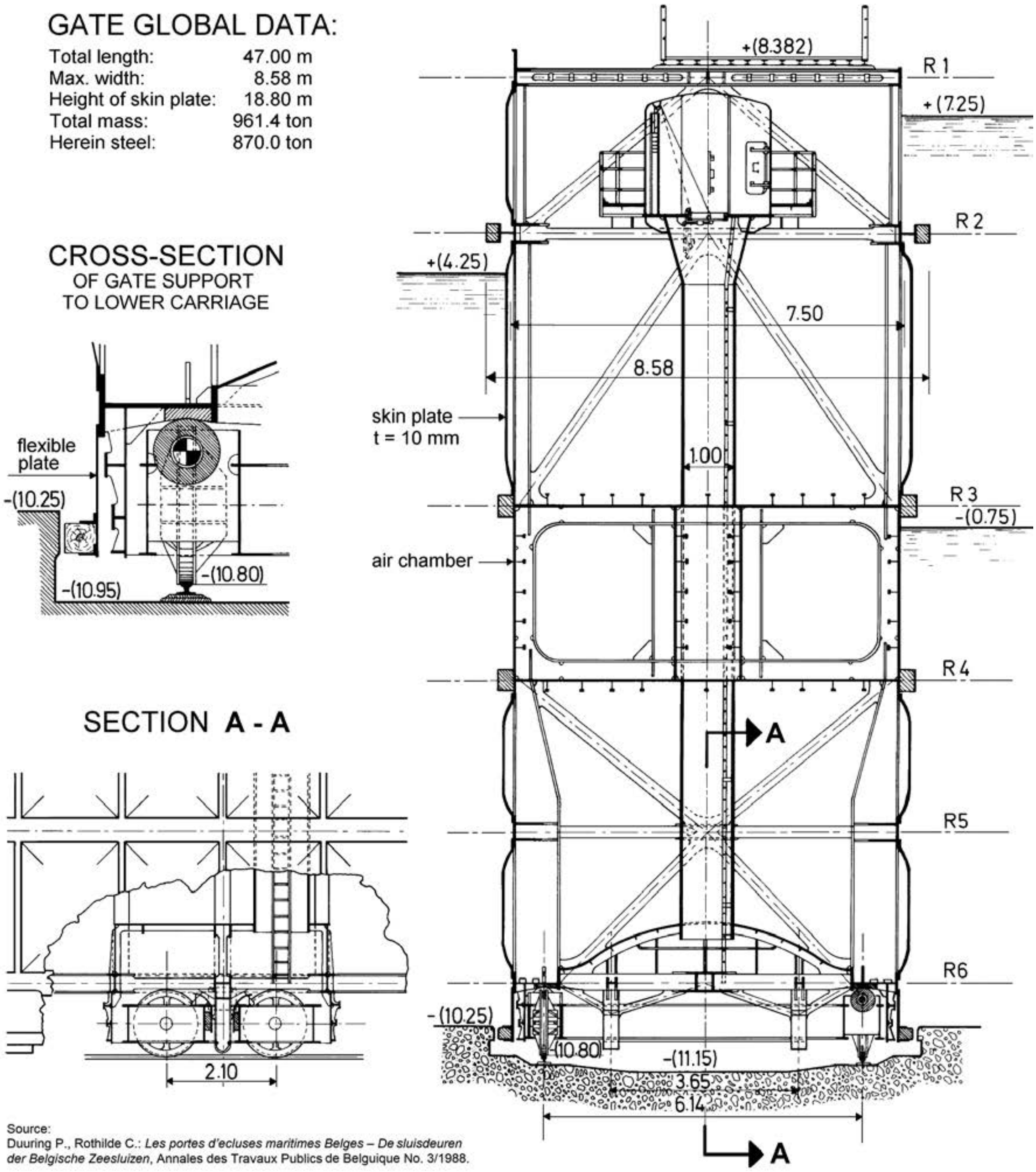


Fig. 11. Rolling gate of the Boudewijn Lock in Antwerp, cross-section [1]

that, however, the Boudewijn Lock gates do not differ much from the currently designed structures. This can be observed in Fig. 12 that shows the assembly of the gate lower carriage at the Berendrecht Lock, which is nearly identical to that of the recently constructed Kieldrecht Lock. The original French notes in this Figure have been preserved for the same reasons as in Fig. 6.

Note the typical components of a rolling gate in the cross-section in Fig. 11, such as the horizontal frames (here 6 in each gate), buoyancy and ballast chambers, and the support to the gate lower carriage. The horizontal frames are here the main load bearing components that transfer the hydraulic load from the skin plate, through the two end frames to the vertical bearings at the entrances to, respectively, to the gate recess and the shallow locking recess on the opposite side of the chamber. Note that the horizontal frames are narrowly spaced in the gate low parts; and widely spaced in the gate high parts, which reflects the distribution of hydrostatic load. Note also that the flat walls of the buoyancy and ballast chamber required additional stiffening, while the buckled plate fields of the skin plate did not.

Gate supports to the carriages belong to the crucial details that determine the performances of the entire system. The typical Belgian solution, with a long list of projects in support of its satisfactory performances, comprises in short the following design principles:

– The gate itself is designed to be self-centering, which means that – under (nearly) equal water levels at both sides – it takes a central position with respect to its rail tracks. This is obtained by applying what could be called "cradle-bearings" at the lower carriage, and suspension devices at the upper carriage.
– Lower carriage (depicted in Fig. 7) moves normally on a wide rail track, with the distance between the rails in the range of the gate thickness. This takes care that

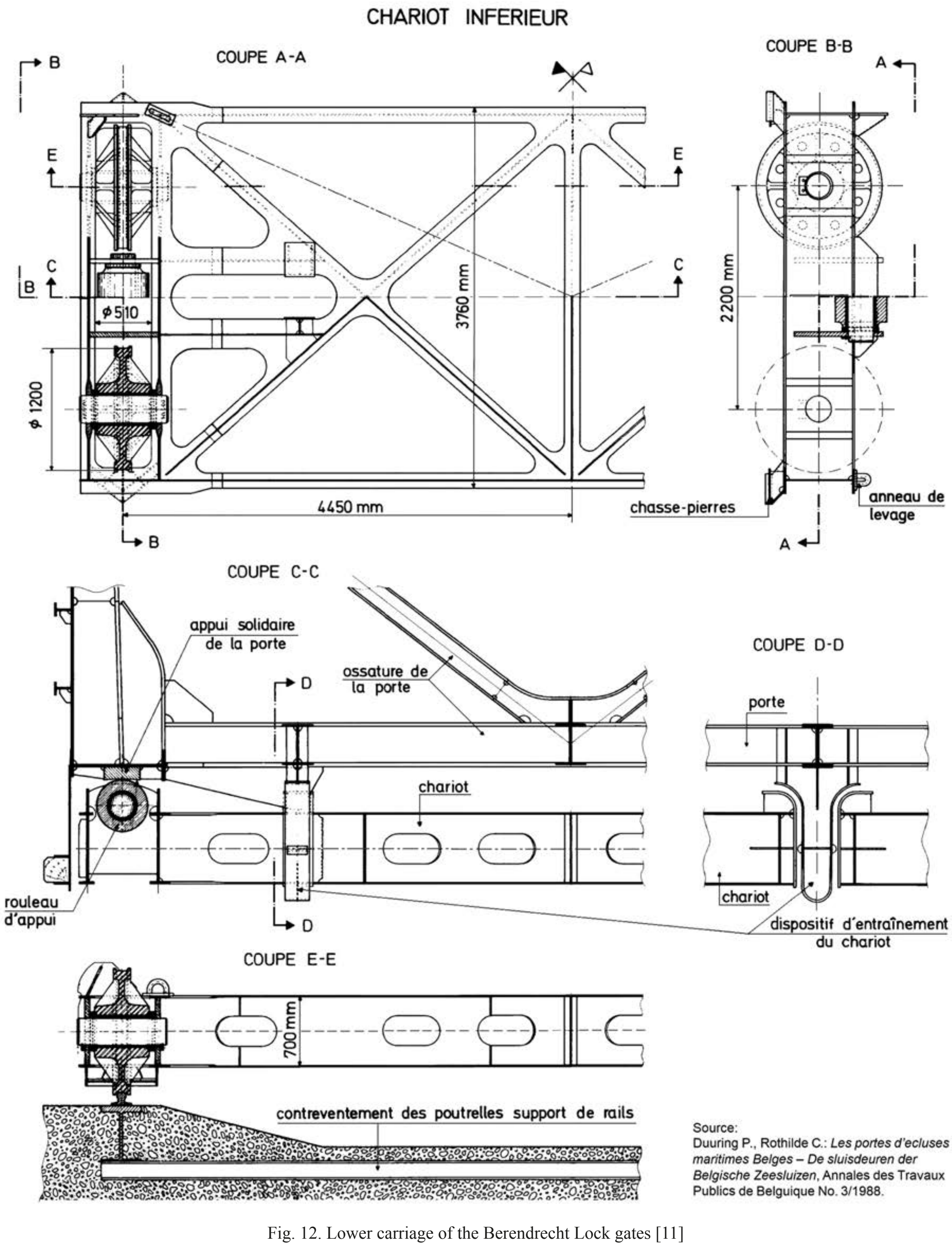


Fig. 12. Lower carriage of the Berendrecht Lock gates [11]

the overturning moment from lateral loads during gate movement (residual water head, waves, salt- and fresh water exchange) does not induce large differences between rail loads.

- The vertical cradle-bearings for the lower carriage (see detail in Fig. 11 and assembly in Fig. 12) and the horizontally dragging pin and socket connection (see detail in Fig. 10 and assembly in Fig. 12) allow for a lateral displacement in the range of 30-50 mm that closes the gate clearances as the differential water head grows. Then it activates the horizontal bearings in the gate recesses.
- The upper carriage moves on a yet wider track, as its rails are supported by the recess walls. The gate connection to this carriage is provided at a cantilevering structure that is fixed to the rear top corner of the gate. The gate is there suspended to the carriage by two pendulums (Fig. 13a). These suspension pendulums are spring-disc hangers of the so-called Belleville type (Fig. 13b). They allow for lateral movement and absorb possible shocks during opening and closing.
- As a result of these arrangements, the typical Belgian-style rolling gate does not require any horizontal guiding

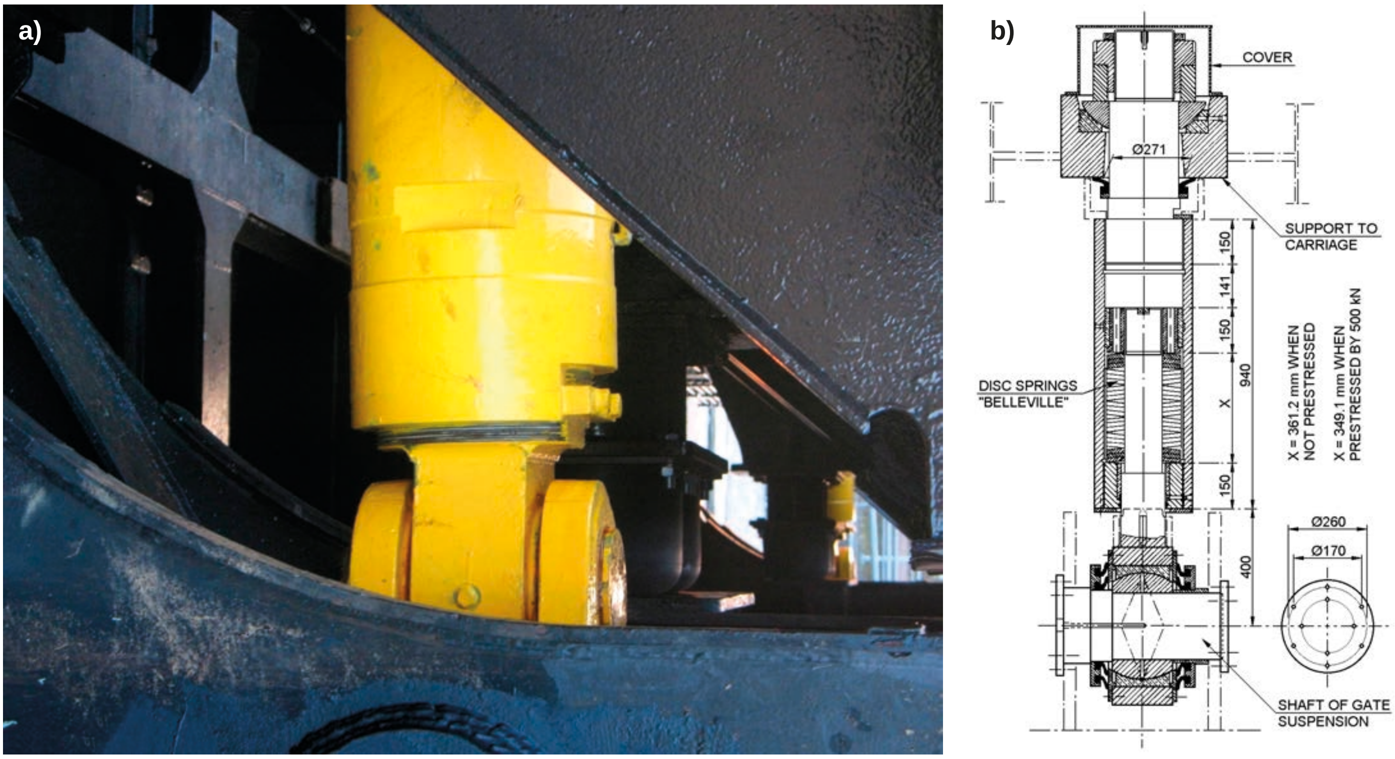


Fig. 13. Suspension of the Zandvliet and Berendrecht Lock gates to upper carriage:
a) spring-disc hangers on gate, photo R. Daniel, b) typical Belleville hanger [1, 11]

devices, neither in its recess nor at the rail tracks. This is the main feature that distinguishes this system from the Dutch-style rolling gates which employ such devices. The other major difference is that the Dutch-style gates move on two lower carriages, so these gates are of the “wagon type”, not the “wheelbarrow type”.

The buoyancy and ballast chambers (also called “air tanks”) have, basically, two functions in the rolling gates:

– keeping the vertical loads on the rail tracks low during the gate movement;
– facilitating gate floatation in both horizontal and vertical position during transport, installation, and removal from the lock.

For optimal performance in these functions, buoyancy tanks are usually equipped with water in- and outlets, and with compressors allowing for dewatering the tanks by pressurizing. It should not surprise that the presence of these tanks sets stringent quality requirements to the welding. It is crucial, that all welds remain watertight, also after many years of service. The tanks must also be accessible for inspection, removal of sediment etc. For these reasons, shafts are usually provided, as shown in Fig. 11. These shafts can be pressurized as well to allow for dry working conditions when the gate receives its maintenance service on the site. In this case, a decompression chamber must be provided for the service crews, which has also been shown in Fig. 11.

Floating and installation of a rolling gate, either as part of a new construction project or after major repair and maintenance, is a very spectacular operation. It attracts the attention of media and is also an emotional spectacle for many professionals involved in the project. These reasons, in addition to the economic interests that are then at stake, justify every effort to make this operation a success. Fig. 14 presents the floatation of the rolling gate of the new Kieldrecht Lock in Antwerp, which has the largest operating lock chamber in the world at the time of writing this article. Observe the subsequent stages of this operation and, particularly, the manoeuvring to enter the gate recess. The latter must be carefully analyzed beforehand (e.g. by 3D computer visualizations) in order to prevent the gate from getting jammed at the recess entrance. One should keep in mind that the gate is always longer than the width of the lock chamber. Ref. [1] gives some practical recommendations in this field.

DRIVE MECHANISMS

Rolling gates may have various drive systems, the examples of some of which have been presented in Fig. 15. While it is certainly advisable to consider a number of possibilities for a particular project, one of them is by far the most frequently used nowadays. It is the wire rope winch system. The most prominent application of that system is, since short, in the Panama Canal Third Set of Locks, where all the 16 rolling gates are driven by wire rope winches. As can be seen in photo (c) in Fig. 15, each single gate is connected to two winches, one on the left and one on the right side of the gate. The winches are coupled mechanically by a torque tube, and have their own electric engine units with gear reducers and couplings that operate in a synchronized manner. When, however, one of the drive units fails, the other unit will still be able to move the gate.

Other than wire rope winch drives of rolling gates shown in Fig. 15 will not be discussed now for two reasons: In the first place, they are rather uncommon or have diverse limitations. The rack and pinion drive in photo (a) performs well, but the lock from this example is only 12 m wide, so that the buckling of the rack free length can easily be prevented. The chain drives

Fig. 14. Floatation of the Kieldrecht Lock rolling gate for installation:
a) bringing in vertical position, b) towing into the site, c) manoeuvring on the site, d) entering the recess, photos by courtesy of Port of Antwerp

of various German lock gates, like the in Bremerhaven North Lock (b) may have operated satisfactory for nearly a century, but this option is outdated and environmentally unfavorable due to the extensive lubrication required. The lateral racks and hydraulically driven pinions of the new IJmuiden sea lock gates (d) have been chosen out of necessity rather than for their proven performance. The reason was the narrow space conditions at this location [7].

This, under normal conditions, leaves no competition for drive option (c). The second reason to disregard the other types of drives is that the wire rope winch drives can be considered a standard choice in the Belgian-style lock gates, which are the leading subject of this article.

The arrangement in Fig. 15c is one of more possible layouts of a wire rope winch drive for rolling gates. Most Belgian locks with rolling gates have a bit different layout of these drives. The electric engines – still separate for left and right side wire ropes – are located close to the centerline of the gate. In this way, there is less need for a rigid torque tube because the torque transmission to both sides has the same elastic parameters. This is especially favored in large rolling gates, the thickness of which may exceed 10.0 m. The most recent example of this arrangement is the drive system of the Antwerp Kieldrecht Lock gates, as shown in the layout drawing in Fig. 16. The gates of this lock have also been presented in Figs. 10 and 14 earlier in this article. These gates are 11.0 m thick and the centerline distance between the two winch drums is nearly 15.0 m.

Typical details of the drive mechanisms arranged as in Fig. 16 are shown in photos in Fig. 17. Photos (a) and (b) have been taken at the Zandvliet and Berendrecht Lock complex; photo (c) is from the Van Cauwelaert Lock. Nevertheless, the depicted details are nearly identical at all rolling gates in the harbor of Antwerp. This is, to some extent, a deliberate policy of both Port of Antwerp and the Flanders' Mobility and Public Works Department (MOW).

One might call this policy conservative, but it results from many decades of experience. Its important benefit is also the standardization of materials, spare parts, maintenance procedures etc., which allows for efficient operation and maintenance at moderate costs. In addition, Belgian engineers keep experi-

Fig. 15. Few examples of rolling gate drives:
a) central rack and pinion, Juliana Lock in Gouda, the Netherlands (R. Daniel), b) chain drive, North Lock in Bremerhaven, Germany (R. Daniel),
c) wire rope winch drive, Panama Canal Third Set of Locks (I. Hermans),
d) lateral rack and pinion driven by hydraulic motor (USACE), comparable to those of the new sea lock in IJmuiden under construction, the Netherlands.

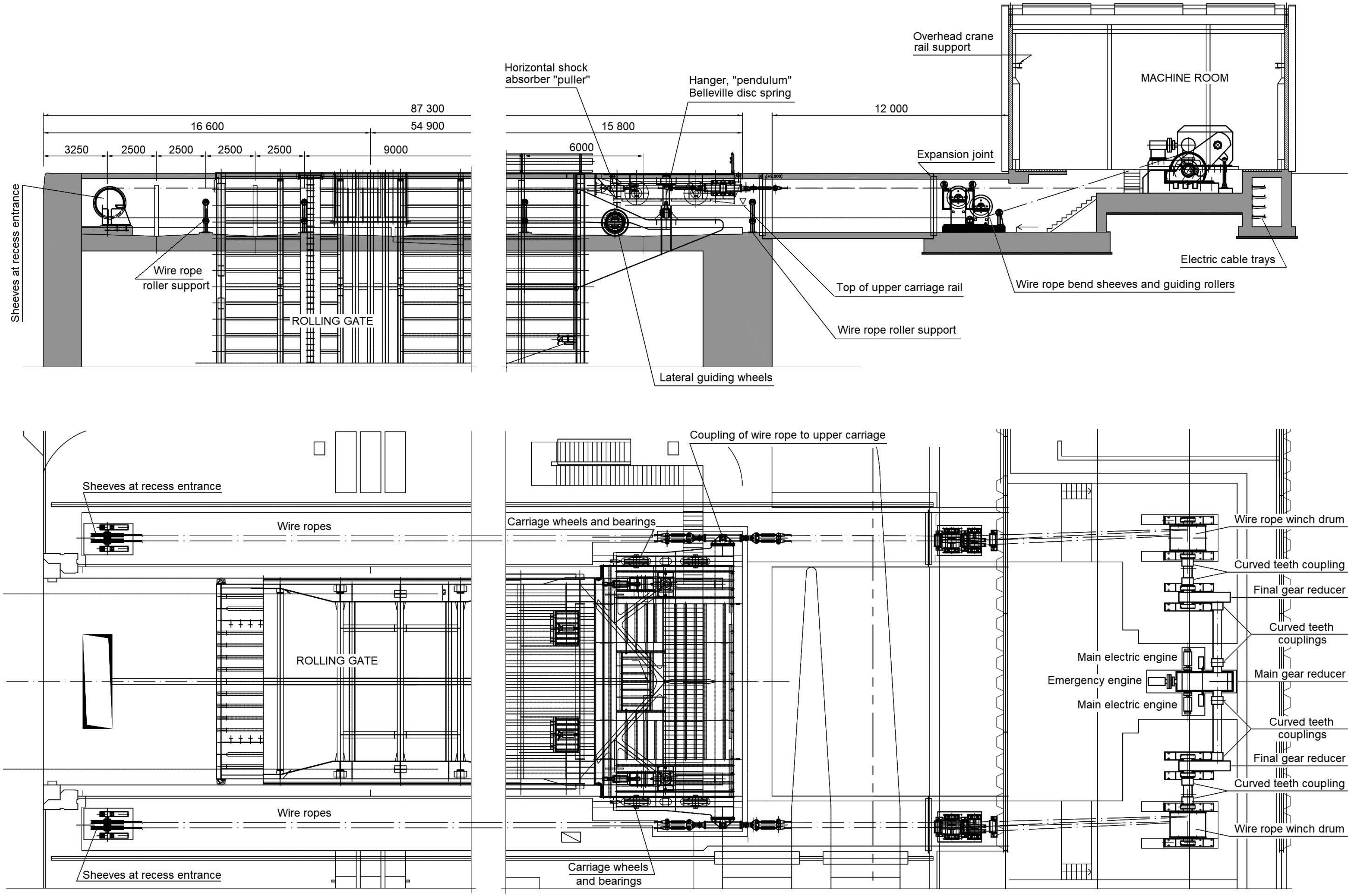
menting with other solutions, either home-developed or proven abroad. An example is the Van Cauwelaert Lock gate with its lateral guiding system and central support of to the lower carriage [6, 16], which deviates from the traditional "cradle-bearing". Such experiments did not, so far, decrease the confidence in the solutions presented above. More detailed discussion on the drive systems of rolling gates, their components and performances can, e.g., be found in [1] and [17].

CONCLUDING REMARKS

This article was inspired by the Polish plans to construct a navigation lock with rolling gates in the canal through Vistula Spit, east of Gdańsk, which is now under construction. The intention was to present a general overview of the technology of such locks in Belgium, one of the Europe's leading countries in this field. Although the conditions of the Belgian North Sea harbors – like tidal and storm water levels, navigation intensity etc. – exceed those of the intended lock project in Poland, there are also a number of similarities. Authors are convinced that sharing the expertise in this field may contribute to the success of the Polish project.

A sea lock project combines the efforts of many parties and disciplines. It also requires the contributions from other than technical fields. This article briefly addresses some aspects of spatial planning and navigation security; and focuses on the crucial components of a sea lock system in view of the main technical disciplines involved: hydraulic engineering, concrete structures, steel structures and mechanical engineering. It is a broad approach, which makes it impossible to discuss all the issues in detail. The authors hope to have presented some most relevant considerations that the designers of sea locks are confronted with today.

The discussed technology and its detailed examples – shown here in drawings and photos – have broadly been followed not only in Belgium. The most recent projects of other countries' sea locks that benefit from this technology include, for example,



Redrawn from: 2e Sluis Waaslandhaven Antwerpen, Deurmechanismen - Samenplan, drawing EMT 3972-1, by courtesy of Port of Antwerp, 20-08-2010.

Fig. 16. Drive system layout of the Kieldrecht Lock gates in Antwerp, after original design drawings

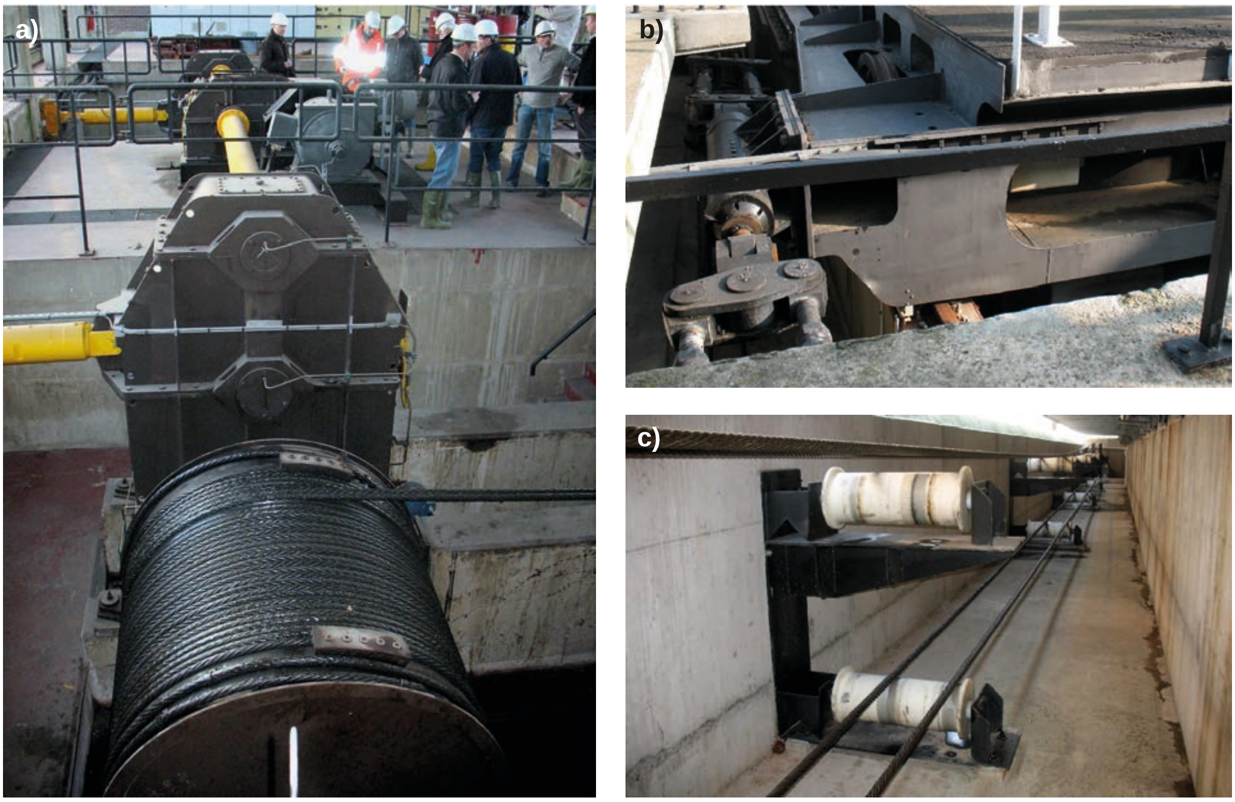


Fig. 17. Typical drives of Belgian rolling gates, details: a) winch drums, gears and engine units, b) rope coupling to the upper carriage, c) wire rope rollers, photos R. Daniel

the Panama Canal Third Set of Locks [18], the new locks in the ports of Seville, Spain, and Terneuzen, the Netherlands. This technology can be classified as very well proven; and deserves to be considered for sea lock projects all over the world.

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