Tension membrane water retaining structures

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Abstract

Since the first recorded use of mitre gates in a canal in Milan during the 15th century there is a consistent aspect to all gate styles. Whether the gate style is mitre, flap, or sector the main structural element is rigid. From the earliest gates that were constructed from structural timber to be followed by iron and currently to steel, gates are all designed to be rigid. Rigid in that the design assumes an elastic deformation, perhaps with plastic design applying appropriate factors of safety with bending moments, shear forces and axial loading: compression and tension. The resulting gate’s structure will utilise the basic structural components of beam, strut and/or arch. These fundamental structural components are well established in not only gate design, but also for building design, bridge design, etc. However, there would be an outcry if the design of a sail for a boat were rigid. Sails are flexible to allow their easy storage, manoeuvring into position and freedom to best respond to wind loading. As there are fundamental similarities to gas and fluid physics why not use a flexible membrane in a structural context to control water levels in maritime uses such as lock gates?

The following sections will consider the established gate forms and their inefficiencies in retaining water levels together with the changing operational maritime environment of such structures. Also to be discussed is the use of an alternative, innovative form of gate structure as a way forward in water retention for maritime uses.

Keywords: gates, flexible membrane, environment, water retaining, locks.

1 Introduction

It is believed Leonardo Da Vinci [1] was the first to design mitre gates in the 15th century when he was advising on the construction of a moat for the defence of Milan. Over 200 years before Da Vinci’s work the Naviglio Grande Canal was
constructed to transport marble to build Milan’s cathedral from 1179 to 1209 [2] and locks were first used to accommodate a fall of 33m in 50 km. Portcullis gates were used prior to the mitre gates in early canals and canalised rivers - if gates were used at all. Often the means of negotiating these manmade barriers was to manhandle the vessel over the barrier.

Manhandling barges loaded with cargo over the barriers was unacceptable and the use of portcullis gates, often constructed with individual planks, was not satisfactory. Rather than the need to lift out the planks the mitre gate, fitted with sluice valves to level the water either side of the gate it could be swung in to and out of position to allow vessel passage. Such was the success of the mitre gate that the design concept was applied to the first commercial impound dock in Rotherhithe, London in 1703 [3]. Since that time the main design concept of the mitre gate has changed little in almost 500 years and is still popular in canals and commercial docks throughout the world.

However, mitre gates do have inefficiencies and with the increased knowledge and understanding of engineering principles in the early 20th century two types of gate, the flap and the sector, were introduced.

Flap gates are normally hinged on a horizontal axis to rotate from its vertical working position to a horizontal position to enable vessel passage and were seen as an advantage for dry docks as the sealing was more effective than the mitre gate. Flap gates have seldom been used as replacement for mitre gates due to the costs involved. To ensure there is no reduction in the draft available to vessels when the gate is open a large recess in the apron of the entrance is necessary to accommodate the box girder as the gate is laid down. Construction of the gate recess and keeping it clear of debris and silt during operation can present difficulties and increase cost as will be discussed in Section 2.2.

The most recent form of lock gate commonly in use today is the sector gate. Sector gates were a major development in gate form with the reference made by Cornick [4] to “the 1920's ... innovation in lock gates on the Sodertalje Canal". In the recent past when new dock facilities were being constructed in the UK, particularly for leisure craft marinas, the sector gate is the preferred option. These gates are unlike most others as they can operate with a head of water in either direction and can be moved whilst subjected to loading. Although the gates themselves are “affordable” the associated civil engineering works are expensive.

2 Inefficiency of “traditional gates”

The three forms of “traditional” gate previously described have performed their function well through the years; however there are inefficiencies that should be considered for the changing operational environment facing tidal gates. In particular, with the accepted rise in sea levels around the global tidal gates are facing the need to exclude higher than previous tide levels as well as the normal impounded water.
2.1 Mitre gates

Mitre gates as illustrated in Figure 1 [5] have been favoured for canals and docks throughout the world since the 15th century but they do have inefficiencies. For example, mitre gates cannot be moved whilst under load therefore sluicing facilities are essential to ensure equal level of water both sides of the gate. In addition, mitre gates are difficult to move during significant water flow in either direction. When the gates are closed during a significant out-flow of water, gates can slam shut causing damage to the gate and the supporting structure. Attempts to close the gate with a significant in-flow rate, or abnormal wave action, can result in the gate being forcibly unstepped. Unscheduled removal of the gate will result in damage to the gate, the operating machinery, the supporting structure, or all three. Such an incident happened at the Port of Sunderland, UK in 1997 and it was decided to reassess the ballasting arrangements of the gate to avoid a repetition of the gate’s unplanned removal in future. Unfortunately such situations are a compromise between too much ballast will increase the rate of wear and tear on the heel post. The alternative of not enough ballast will increase the risk of an unscheduled unstepping of the gate.

Perhaps the most significant failing of the mitre gate in a changing operational environment is its inability to resist a reverse head. Numerous attempts have been made to engineer a solution to this failing as demonstrated in Daniel and Vrijburcht’s paper [6] documenting the efforts made by Dutch engineers. Wherever efforts have been made to enable mitre gates to resist a reverse head there has been significant lack of success. For example, the Kings Lynn area in Norfolk was at risk from flooding and one route for the flood water was through the tidal lock entrance to the dock. The dock owners, Associated British Ports accepted the impracticality of modifying the existing mitre gates and decided that the existing outer mitre gates would be replaced with sector gates. Although the costs of the sector gates was approximately half the cost of replacement mitre gates the civil engineering works necessary to accommodate the sector gate recesses was around ten times the cost of replacement mitre gates. Not surprisingly, conversion of a mitre gated lock to a sector gate system is not a regular event.

Mitre gates face another major difficulty in terms of current operational environment in that many lock operators have reduced maintenance to the minimum in an effort to save operational costs. As a consequence of this approach any problems that could be solved during a scheduled maintenance event are left until the problem significantly affects the operational efficiency of the system. When it is evident major maintenance is required the cost of correcting the problem(s), if possible, is significantly more expensive than it would have been if it had been attended to earlier. In addition, the majority of mitre gate systems have no facilities to deal with the consequences of wear and tear. Due to the size, hence weight, of such gates the cost of removal of the gate and their installation once repaired will often be significantly greater than the cost of the repair work. For the duration of such repairs the operations of the dock are significantly affected, and likely to cause substantial financial losses.
It would be a reasonable conclusion to say that mitre gates are not suited to meet the challenge of rising sea levels or today’s commercial environment.

2.2 Flap gates

The introduction of flap gate (as indicated in Figure 2 [7]) was seen as an improvement on the mitre gate, however it would wrong to suggest flap gates are without fault. Early flap gates functioned by a single winch that operated through a number of pulleys to effectively pull simultaneously on both sides of
the entrance to raise the gate. To lower the gate the hinge point would be located forward of the centre of gravity of the gate such that it would fall back by gravity but under control from the winch system. A weakness of a flap gate operated by the winch system is that if the gate movement down to its parked position is blocked by debris or silt, the winch cannot drive the gate into the recess. As a result of this incomplete operation there would be reduced draft and a ship could strike the gate. Efforts have been made to measure where the gate is during the opening procedure but with no notable success. Use of a suitably sized hydraulic cylinder is an alternative means of opening and closing the gate. Should there be an obstruction the hydraulic cylinder can drive the gate downward but with sufficient control to minimise the risk of damage to the gate or the apron.

Unlike mitre gates flap gates can resist a limited reverse head by being locked in position. As for wear and tear, the failings of the mitre gate are compounded in the flap gate due to its size being significantly larger; therefore removal is more of an engineering challenge.

2.3 Sector gates

Water pressure will always act perpendicular to the surface it acts on. In nature, structures that retain fluids seldom have a straight, flat surface and the curved face of the sector gate is an example of how to take advantage of this phenomenon. As the skin plate on a sector gate is curved and concentric to the hinge point all water loading ultimately pass through the hinge point with no eccentricity.

Although there are some difficulties, sector gates can be manoeuvred in a significant flow of water in either direction as illustrated in Figure 3 [8]. This means the impounded water can be higher or lower than the external water level and the gates can be opened or closed with an incoming or outgoing flow of water. No other style of gate has such features as an inherent part of its design concept.

However, sector gates do have disadvantages, such as the recess necessary to store the gate when the entrance is open to allow passage of vessels. The plan area required to accommodate these structures is large and can be obtrusive to other dock functions. Additionally, the large recess can act as a settlement lagoon resulting in a deposition of silt that can build-up and restrict the gate's movement into the recess.

Perhaps the most significant recent use of a sector gate is for the New Waterway Storm Surge Barrier [9] that provides protection for the Port of Rotterdam, Holland. Unlike a conventional sector gate arrangement this surge barrier will allow a leakage under and around the gate as the intention is reduce the risk of flooding not to prevent a rise in water level within the confined area of the dock. The risk of flood is directly associated with the tide which is limited in time, therefore the lack of absolute watertightness is less important.

Of the three gate styles being considered sector gates are the most suited to cope with the raising sea level, however the cost of construction is often prohibitive as is the cost of major maintenance. Spare mitre gates have been
held in storage in a number of ports but not for flap or sector gates due to the cost and storage difficulties.

Figure 3: Indicative arrangement of a sector gate.

Figure 4: Extract of US Patent 5,154,537.
3 Tension membrane water retaining structure

Although the traditional approach of gate design makes use of standard structural forms (beam, arch and struts) that are satisfactory in “normal” structural uses such as buildings or bridges the loadings induced by water are quite different. Water, and gas pressure, always acts perpendicular to the local surface, i.e. a perpendicular in local terms rather than globally as gravitational forces. Given the successful use of flexible structures to act as sails perhaps a flexible structure would be more effective in coping with water loading. As strange as this may seem a number of flexible water retaining structures have been patented to mark their innovation:

1. Patentschrift Nº 71864 Klasse 84a Gruppe 4 01 dated 1942
2. United States Patent Nº 2,593,969 dated 1952

Item Nº 1 was a temporary, foldable water barrier meant for emergency purposes to collect water in a small channel such as a stream and was not intended to be a permanent feature nor moveable. Items Nº 2 to 4 are not flexible in that they are vertically spanning thin shells, not membranes, however item Nº 2 is formed into a circular form rather than straight. Item Nº 5 (as indicated in Figure 4) is a flexible structure comprised of a membrane that deforms in line with the water and air pressure applied. In this structure a compressed air pressure inflates the membrane to rise from the concrete apron (12 in Figure 4). When not in use the chamber is deflated and the membrane collapses to lie on the apron. Pumped water can be used in place of compressed air to achieve the same effect. Despite the positive advantage of there being flexibility in form thereby responding directly to the water pressure a significant negative aspect of this structure is the extensive foundations in the apron. Replacement would require dewatering of the immediate area or the use of divers – both are expensive options.

The Tension Membrane Water Retaining Structure (TMWRS) is a concept covered by international patent PCT/GB2002/005579. As an alternative to the traditional gate systems the TMWRS has one major difference in that it is flexible at all stages of its life. However, the objectives of the TMWRS and traditional gates are intrinsically the same, i.e. to retain a static, and to some extent dynamic, water level to aid shipping.

The TMWRS is most like the 1942 German Patent in that there are strong points but rather than being a temporary static device the TMWRS is an alternative gate style therefore is permanent and movable. To date the concept has been tested as a scale model as indicated in Figure 5. To allow vessels passage the TMWRS is driven downward to lie on the apron in a concertina fashion as indicated in Figure 6.
Retained water

Figure 5: TMWRS tank.

TMWRS under load

Figure 6: TMWRS in “open” mode.

Figure 7: Indicative arrangement of TMWRS.
The TMWRS is flexible and will be responsive to the water loading to help form and maintain a watertight seal. Figure 7 illustrates the proposed operational arrangement of the TMWRS. As the materials forming the TMWRS are man made there is less concern of natural decay. Indeed the non-biodegradability of the material is advantageous as there is less maintenance required. Various forms of membrane were tested including polyethylene from a waste disposal bag, a “Goretex” coated textile used for rainproof jackets and finally polyester sail cloth. The most successful was the polyester sail cloth where leakage was minimal and was the most operationally efficient. The system has been successfully analysed by manual calculations and by computer assisted methods as indicated in Figure 7.

![Figure 8: CAD Image of TMWRS.](image)

Most traditional gates, with the exception of the sector gate, cannot be moved whilst retaining water, but equalized water levels are necessary such that vessels are able to pass through a lock thus a form of sluicing is required. As the TMWRS moves downwards when opening this allows water to flow over the top and could be seen as a form of sluicing. Arguably the dynamic effect on vessels within a lock would be less extreme than normal means of sluicing.

To move the TMWRS a single winch powers a continuous length of steel rope, or chain, to ensure the synchronous movement of both sides of the gate. All other gates require a more complex operational system to ensure the effective operation during opening and closing.

The flexibility of the TMWRS has the advantage to being able to move to meet the static support structure to form an effective watertight seal from the applied hydrostatic pressure. In addition the flexibility of the TMWRS will allow a replacement gate to be held in storage occupying a space significantly less than that normally required for traditional gates.
4 Conclusion

Development of a modern alternative to the traditional mitre gate as used in canal and dock locks throughout the world is long overdue. With raising sea levels there is a necessity for existing tidal locks to be able to cope with the resulting change to operational conditions. Alternative structures, such as the TMWRS, will be necessary as many of the existing gate systems are unable to cope.

To progress the development of the TMWRS a full scale prototype is planned to be installed during late 2005 as a divider gate in a drydock. As there are no previous examples of this structure, thereby no design standards, an independent design check is currently being carried out. Development of materials for the membrane will also be required to meet the demands and constraints of the operational environment.

From a value engineering perspective the TMWRS is estimated to be approximately 50% that of a traditional gate over a normal gate generation period of 50 years. No doubt Da Vinci suffered concerns when he proposed the mitre gate but defence is a common factor and time is limited therefore change is necessary.

References