Review and Optimisation of the UK's Canal Locks

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Abstract: *The UK canal lock system was first constructed over 210 years ago. It enabled a revolution within the industrial sector, allowing goods to be transported cheaply. This paper reviews six engineering focal points of the use of the pound lock – the mechanics of the lock gearing mechanisms, the forces acting on an opening gate, forces induced on the hinges of a mitred gate, water loss, force on a boat hull from water emitted from a weir and using CFD to model the water flow through a paddle culvert. The results from these investigations were reviewed and seven areas were highlighted for design improvements - safety catches (pawls), opening mechanism, reduced water usage, angle of bywash, use of turbines in paddle openings, modular design and materials of the gates. Concept designs were formulated. A graphic was created that incorporate all of the design changes proposed. The results are evaluated and further work recommended.*

Keywords: canal locks, lock gearing, forces, water flow, turbines

Introduction

The canal system forms a part of this country's heritage. Now used only rarely for goods transport, the network is as busy as ever, the leisure and tourism industry have given the system a different purpose. A new 20 mile canal is currently being planned in East Anglia, to connect the Grand Union Canal to the river Great Ouse (Landers, 2002). The role of maintaining the 2,200 mile network, previously British Waterways, a public corporation, was recently taken over by the Canal and River Trust (C&RT) on the 12th June 2012 (UK CANALS NETWORK, 2012). Whilst the C&RT receive fixed funding from the government, it is their aim to become self-sufficient. This article aims to review the current lock system in order to reduce maintenance costs, running costs, health and safety risks and improve usability, so reducing the financial pressure on the trust, enabling the public more access to the canals and allowing more donations to be spent on restoring the rest of the UK's waterways.

Review of Existing Knowledge

As this paper investigates navigational locks solely in the UK, it has a limited scope. The design of the pound lock has not varied much since the 1800's and while there is much concerning the colourful history of the canals, there is very little specific academic research. One element that has been identified is work undertaken concerning the Hawser force criterion, which attempts to define the maximum amount of turbulence the water in the lock chamber should undergo, in order to restrict boat movement and force in any mooring lines. There have been various methods of defining Hawser's force criterion, initially created in terms of the hydrodynamic force on the boat hull. This however, has limitations as it does not take into consideration the way that a boat can be constrained to the side of a lock chamber. UK canal locks have fixed bollards at the side of the chamber so that a boater can loop their ropes around and loosen them as they descend, yet keep their boat close to the side of the lock.

Partenscky (1986) and Vrijburcht (1994) included the effects of different mooring ropes by equating the system as similar to a mass and spring system. Their work was then taken up by Rijkswaterstaat-Bouwdienst (2000) to be applied to locks with floating bollards.

Whilst Partenscky and Vrijburcht's work did focus on inland canals and so holds closer relevance to this article than locks designed for large, sea-going vessels, it is worth remembering that the Panama Canal is an inland canal. The Panama is of a much greater scale than any present in the United Kingdom. That is not to say that the research completed on Hawser criteria is not relevant to this article. It demonstrates the need to be aware of the effect of turbulence and important of water flow.

This limitation of critical research papers rather than historical accounts meant that this article was led to undertaking engineering analysis from primary research in the form of experiments and an interview with a member of the C&RT. Secondary research was also used, adapting proven equations from physics and engineering textbooks to suit the situation and scope at hand.

Analysis

Lock gearing

An understanding is required as to the different types of gearing mechanisms present on the system, used to raise the paddle and allow water in or out of the lock. Three different gearing mechanisms were identified: traditional, worm-gear and hydraulic.

Traditional lock gearing is the most prevalent and is based on a rack and pinion device. A windlass is used to rotate the spindle which is connected to a series of cogs and a toothed strip of metal rises out of the top of the lock gear. This is connected to the paddle and so as it is raised, water is allowed to flow through the culvert. There is also a safety mechanism, a pawl that engages with the teeth of the rising strip of metal preventing it from dropping back down in the event that the windlass become disengaged or is released.

Worm-gear lock gearing is present on the system still, notably at Hatton locks (Warwickshire). It is commonly judged to be hydraulic but this is incorrect. The design behind this type of system is to allow users to be able to raise a paddle easily, hold it at an open position and when required, allow gravity to close the mechanism safely to reduce human effort. A rod is threaded in the middle for a considerable distance. One end of this rod is connected to the paddle which opens or closes the valve. Approximately half way up the chimney, at about waist height, there is a spindle which extrudes out of the casing. This spindle can be rotated with ease using the windlass and is connected at the other end to a cog. This cog then fits into a circular set of teeth around the perimeter of the inside of the chamber, supported by a casting. There is a thread inside the set of teeth which engages with the threaded section of the rod, therefore as the teeth rotate round, the rod is raised or lowered without rotating itself.

Hydraulic lock gears have been used in the past but there are few specimens left. They are distinguishable generally by their round geometry and position atop balance beams. They are operated the same way as traditional lock gearing, using a windlass and rotating clockwise to raise the paddle. An oil operated hydraulic pump is contained inside each chamber, with the pressure being transferred via small tubes. The tubes are connected to a double acting piston with oil chambers at each end. The 'pump' pulls the oil – hydraulic fluid – from one end of the piston and forces it into the other. This action raises or lowers the paddle. This type of lock gearing has been dramatically reduced in numbers as it cannot be lowered quickly in an emergency. If anything goes wrong in a lock, the first action should be to stabilise the water levels. In contrary to the other two types, hydraulic gearing takes as long and as much effort to lower, as it does to raise it. For this reason, they are generally only seen on lift bridges where speed of return is not crucial.

Human effort required to operate locks

An empirical method was opted for to solve the equation:

$$Force_{human} = Inertia_{beam} + Inertia_{gate} + Pressure\ Differential\ (of\ water) + Friction\ (of\ hinge)$$

Several methods to record force were considered: a rope attached to a Newton meter, breaking down body weight with vector analysis, a compressive load cell, it was decided that a simple approach was best. A calibrated pair of bathroom scales were chosen, mounted on a 32 x 32 cm wooden base with a duct tape loop attached. This loop attachment was decided due to the need for the apparatus to fit lock beams of varying sizes and the high possibility that the beams would be either wet or icy (readings taken in the UK in December).

Two experimental procedures were undertaken. The first captured the highest initial force required to move the beam, whilst the second measured the time taken to open the gate under constant force. Both procedures were repeated on top and bottom gates (due to water levels, these gates were on different locks – Lock 1 and 3 of the Aston flight, Birmingham).

For the initial force procedure, three readings were taken, allowing time for the water levels to stabilise between each one. The reading in kg was then converted into Newtons and shown in Table 1 - Opening force.

	Reading 1 (N)	Reading 2 (N)	Reading 3 (N)
Lock 1 (bottom gate, empty lock)	242.3	230.5	245.2
Lock 3 (top gate, full lock)	96.1	82.4	97.1

Table 1 - Opening force

As Table 1 shows, Lock 1 required approximately 1.5 times more force to open than Lock 3. Lock 1 was the empty lock, in which the larger bottom gate was used. This implies that the weight of the gate plays a significant role.

The constant force procedure was a little trickier to determine readings for. A video was taken of the bathroom scales display during each opening. This was then reviewed and the readings were taken at a 1 second sample rate.

Lock 1 (bottom gate, empty lock) required more force to open despite having less water to displace. Both lock gates are constructed of oak, which has high buoyancy properties. This enabled Lock 3 (top gate, full lock) to float slightly and not hang off the hinges. It supports the

previous hypothesis that the weight of the gate has more effect on human force required than water pressure.
The data procured from the procedures above was used to identify elements of equation 1. The average human power required to open Lock 1 was determined using a simple work done calculation, multiplied by the time taken to open the gate.

The inertia of both the balance beam and the gate itself were calculated using an inertia equation design for cuboids rotated about the centre of one of their shorter sides (Hills, 2003).

$$Moment\ of\ Inertia = \frac{m}{3} \times \left(L^2 + \frac{1}{4} \times W^2\right)$$

They were also converted into power by multiplying the result by the angular velocity.

Modelling gate rotation of 90° through the water was out of the article scope, so instead it was reasoned that the largest water force would be applied at the end of the gate, as it has to displace the most water. At the end of the gate, the force is deemed to be close to the force of a plate in perpendicular flow (a radius of infinity). The force would then decrease in an unknown curvature, reaching 0 at the hinge. The velocities at the point of contact with the beam and the end of the gate were calculated and the equation below used (Çengal and Cimbala, 2006).

$$F_D = C_D \times A \times \frac{\rho \times V^2}{2}$$

The gate was divided into 10 sections and iterations were taken of this equation, using the velocity calculated in the centre of those section. The results were used to plot the distribution of the water force on the underwater section of the gate. The start and end values were also included on the plot. Using the Trendline tool in Excel, an equation of the curve was obtained:

$$y = 7.2778x^2 - (2 \times 10^{-13})x + (9 \times 10^{-14})$$

This equation was integrated and multiplied by time to give the power of the water pressure on the gate.

The final element left to identify was the friction in the hinge of the gate. Balancing the equation left a high value for this which implies that there may be an unidentified force acting on the gate.
The results of these investigations are shown in Table 2.

Lock Number	Human Force (kW)	Inertia of Beam (kW)	Inertia of Gate (kW)	Pressure Differential (kW)	Friction Force (kW)
1	21.66	2.28	1.12	1.116	17.44
2	14.13	1.16	0.356	1.384	11.23

Table 2 - Forces on a Lock Beam

A few considerations were noted. There was ice present on the canals on the day of experimentation, although broken up fully; the increased density of the water could have had an effect. The hinge had some slack in it which allows the lock gate to hold its position fully open or fully closed. This was not taken into consideration. Simplifications were made in this section of investigation due to scope limitations. Although a perfect balance did not occur, this section has given an insight into the forces that are present on a gate and those that could be reduced (i.e. inertia).

Net water force for a mitre gate lock

This section of the paper evaluates a full lock full and determines the forces on the downstream gates, specifically the reactions in the hinges. The diagrams and calculations below have been adapted from an example from (Paul, Mukherjee and Roy, 2005); using measurements of realistic water levels and lock sizes, taken from Claydon Top Lock in Oxfordshire.

Hinge	Reaction (kN)
Top	25.26
Bottom	56.34

Table 3 - Reaction Forces on Lock Hinges

It is interesting to note that the bottom hinge had more of a reaction force present when the gates are closed that the upper hinge. This means that the material selected for the hinges must be capable of handling that force. This set of calculations required adapting as they had been constructed on the assumption that lock gates have two hinges a set distance away from the base of the gate. In fact, lock gates are constructed using a pin and pintle arrangement. This in effect creates the base hinge at the bottom of the gate.

Effect of locks from an environmental view

At first glance, locks appear to be entirely self-sufficient. They require no electrical power to raise the paddles, or open the lock gates. This is all done via human work. However, there are hidden costs involved. One of the largest of the costs is due to water maintenance. Locks are at their most efficient when an equal number of boats are travelling in opposite directions. This means that two boats can change level on one lockful of water. If however, there is constant stream of traffic in one direction, then only one boat changes level with each lockful. On top of this well-known issue, which is managed by lock-keepers where able, is the addition of gate leakage. A small leak can empty a lock over several hours, which can have a severe detriment on the above pound. As water cannot travel uphill, where a boat is ascending or descending all water will be emptied into the lower pound. This can leave summits lacking in water. In some places, pumping is required to raise the water back up to its previous level. This is known as back-pumping. Table 4 - Pump Types demonstrates the number of pumps in use on the UK canal system in 2011. The majority of pumps on the system are designated for back pumping.

	Count
Groundwater pump	4
River pump	14
Back pump	45
Storm water pump	1
Reservoir pump	5
Sea pump	1
Unknown	0
Total	70

Table 4 - Pump Types (Gow and Comerford, 2012)

Smart meters have now been prioritised as this allows remote monitoring. This in turn allows Canal and River Trust to be reactive with their water management system, identifying and resolving issues quickly.

Table 5 highlights the need for this research investigation. It does not include data for all pump sites as only comparable sites over 2010 and 2011 could be used. Even so, the costs are startling. The increase over the year could be due to a drier season, and hence more requirement for pumping, as well as an increase in tariff costs. If a small amount of water can be saved at each lock, and so reducing the requirement for pumping, then the costs involved could be reduced dramatically.

	No. sites compared	2010 data***	2011 data	Difference %
Total quantity pumped (Ml)	36	83,913	122,572	+46.1
Total electricity consumed (kWh)	56	8,393,825	9,739,860	+16.0
Total electricity costs (£)	56	710,455	890,915	+25.4

**** differs to figures given in 2010 report as corrections have been made and some pumps removed as they were not operational pumps.*

Table 5 - Year to year comparison data (Gow & Comerford, 2012)

Side ponds are a useful addition to lock structures. They reduce the amount of water used in each level change by half. They are situated at exactly half the height of the lock, which enables a full lock to empty half of its capacity into the side pond and then eject the rest into the lower pound as usual. When a boat ascends, the lock can be filled halfway with water from the side pond reservoir and then topped up with water from the upper pound. Small reservoirs like this can hold enough water for several boats to travel one way without being drained. They are then topped up by boats descending. There are limitations with the use of side ponds – in addition to a requirement for space when constructing, users must be educated in how to use them properly in order to avoid flooding or draining of pounds, locks and surrounding areas. Furthermore, they must be kept clear of weeds, especially around weir areas to ensure that water can flow freely. It has not been possible to obtain construction costs of a side pond, although they have been reasoned out to include cost of land, cost of waterproofing both walls and floor and on-going maintenance costs. While appearing the costly choice, electricity does hold the benefits of being more convenient and controllable. It is only necessary to use when required and does not need user's interaction in order for the canals to benefit from it.

Effect of a bywash (weir) on canalboats

In sections on the Llangollen canal, there are bywashes at the base of locks which are angled at 90° to the canal and can force a boat into the lock wall, causing damage. This section investigates the force generated by a weir at 90° to a boat hull, beginning with the volumetric flow rate over a weir using equations adapted from (Çengal and Cimbala, 2006). The measurements, included in brackets where relevant, are based on the weirs present of the Llangollen canal, at the border between Wales and England.

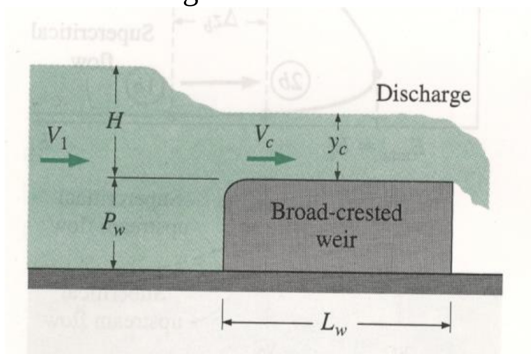

Figure 1 - Flow over a broad crested weir (Çengal and Cimbala, 2006)

$$\dot{V} = Volumetric\ flow\ rate$$
$$A_c = Area\ of\ the\ channel$$
$$y_c = Critical\ depth$$
$$b = Width\ of\ weir\ (6m)$$
$$\dot{V} = A_c \times V$$
$$V = \sqrt{g \times y_c}$$
$$\dot{V} = y_c \times b \times \sqrt{g \times y_c}$$
$$\dot{V} = b \times g^{\frac{1}{2}} \times y_c^{\frac{3}{2}}$$

Energy equation between a section upstream and a section over the weir for flow with negligible friction:

$$H = Weir\ head\ (0.15\ m)$$
$$P_w = Height\ of\ weir\ block\ (0.5\ m)$$
$$H + P_w + \frac{V_1^2}{2 \times g} = y_c + P_w + \frac{V_c^2}{2 \times g}$$

Cancelling P_w from both sides and replacing $V_c = \sqrt{g \times y_c}$ gives:

$$y_c = \frac{2}{3} \times \left(H + \frac{V_1^2}{2 \times g}\right)$$

Substituting this into the previous equation gives:

$$\dot{V}_{ideal} = b \times \sqrt{g} \times \left(\frac{2}{3}\right)^{\frac{3}{2}} \times \left(H + \frac{V_1^2}{2 \times g}\right)^{\frac{2}{3}}$$

This gives the ideal flow rate but does not take into account the effects of friction. An experimentally determined weir co-efficient $C_{wd,\ broad}$ is included to modify the expression.

Where:

$$C_{wd,\ broad} = \frac{0.65}{\sqrt{1 + \frac{H}{P_w}}}$$

$$C_{wd,\ broad} = \frac{0.65}{\sqrt{1 + \frac{0.15}{0.5}}}$$

$$C_{wd,\ broad} = 0.57$$

The upstream velocity $V$is generally very low and can be disregarded. Giving:

$$\dot{V} \cong C_{wd,\ broad} \times b \times \sqrt{g} \times \left(\frac{2}{3}\right)^{\frac{3}{2}} \times H^{\frac{3}{2}}$$

$$\dot{V} \cong 0.57 \times 6 \times \sqrt{9.81} \times \left(\frac{2}{3}\right)^{\frac{3}{2}} \times 0.15^{\frac{3}{2}}$$

$$\dot{V} \cong 0.3387\ m^3/s$$

This is applicable for weirs where: $2H < L_w < 12H$.

Force on boat hull from weir flow rate

A bywash takes water in at a weir above the lock and releases water lower down from an output weir. The output weir is often a different shape and size to the input weir. An output weir had been measured as 1 m wide by 0.5 m tall. The flow rate has been calculated as $0.3387\ m^3/s$. If this water is then ejected from a small area into a lower pound in the canal, it can be approximated to a jet acting on the hull of the boat. The hull of a boat is a generally a flat plate at a small angle of approximately 10°.

Velocity of jet:

$$V = \frac{\dot{V}}{Area\ of\ Nozzle}$$

$$V = \frac{0.3387}{1 \times 0.5}$$

$$V = 0.6774\ m/s$$

According to Hannah and Hillier, 1999, the force of a jet on an inclined plate can be calculated from:

$$F = \dot{m} \times v \times \cos\theta$$

$$F = \rho \times A \times v^2 \times \cos\theta$$

$$F = 1000 \times (1 \times 0.5) \times 0.6774^2 \times \cos 10°$$

$$F = 225.95\ N$$

The value of 225.95 N calculated is a rough guide for a very specific situation. However, it does stand to demonstrate the effect of 15 cm of water flowing over a weir at the top of a lock can have when flowing out of the bywash at the base of a lock, at a 90° angle.

This force may seem slight in comparison to the weight of a fully laden 20 tonne boat, but it is significant enough to push the boat sideways into the bank or a lock wall. This value again is an underestimation as it has not taken into consideration the gain in kinetic energy the water will experience after dropping the height of the lock. It is relevant however, to show that bywash angles can have a noticeable effect on waterway users.

Flow of water through a culvert

The flow of water through a paddle opening in either a gate or through a culvert in the ground has a large amount of water travelling through it. This section investigates the velocities that culverts can expect to experience. The engineering analysis software “ANSYS”, was used to model and investigate. The measurements from Lock 1 in the Aston flight were used to create the geometry. Representations of the lock were created either side of a gate paddle opening. The reason that two identical sections were used either side of the paddle opening was to allow the model to demonstrate both water entering /

leaving a lock. The mass flow was calculated by multiplying the volume of the lock, by water density and then by the time taken to empty. This mass flow rate is an approximation and will only be relevant at the beginning of the lock emptying. This is because as the lock becomes empty, the mass of water will lessen and therefore the flow rate will reduce. The results of this model should be used to give an idea of the maximum velocity that may occur in this situation, expecting the mass flow rate to reduce to 0 kg/s as the lock empties.

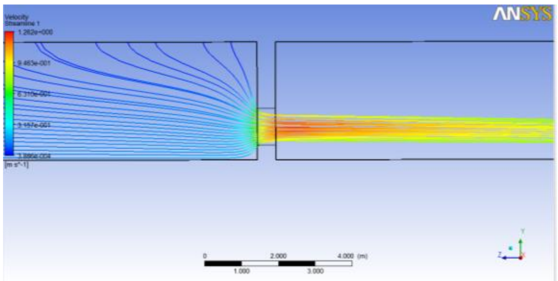

Table 6 - Velocity streamlines through culvert

In comparison to the water speed through the culvert, the speed of the water is almost halved by the time it hits the other end of the lock. This is still enough to cause some turbulence and affect the motion of the boat. However, as the boat is in a contained space, it is likely that this turbulence would only push the boat backwards. This will probably go unnoticed as the flow directly from the culvert is pushing the boat forwards with more force. The maximum velocity, calculated using this approximation model in ANSYS, is 1.262 m/s.

Maintenance costs

The Canal and River Trust have many demands on their time and resource. One of these is carrying out a structured series of checks on the locks, on a cyclic basis called “planned preventative maintenance”. These checks are designed to keep the locks running with minimal downtime. Checks include: greasing collars and paddle operation mechanisms, tightening bolts, checking and adjusting collar and anchors, removing vegetation from lock gates, cleaning lock signs, painting cill markers, cleaning lock ladders, edging coping stones and bollard plinths, removing vegetation and debris and painting steel balance beams, steel/timber lock and approach bollards. Whilst it would be preferable to eliminate some of these necessary maintenance tasks, it seems likely that many will remain after the proposed design changes. It is important however, to highlight that this is just one of the demands on the Canal and River Trust’s time. With the completion of this article’s aim, the running costs of locks should be reduced and therefore further resource can be used in maintenance.

Health and safety issues

There are several well-known health and safety issues with using locks. Not all can be eliminated but by identifying them and highlighting them to users, risks can be reduced. Common health and safety risks are listed below.

Fenders becoming wedged in lock gates – Should a user’s fender become wedged in the gaps in a lock gate, this can easily tip the boat. If the front of the boat is tipped so far that the water vents on the front deck become submerged, the boat will sink. This can not only cause injury and death in the worst cases, but it also disables the lock until a crane can lift the boat out, a costly removal process.

Bent rudders – If a boat rudder hits the concrete cill as it is descending in a lock, it can damage both the cill and the boat. In worst cases, the boat will tip forward and if sufficiently angled, will fill with water and sink. A boat with a bent rudder cannot steer properly.

Windlasses – Some lock gearing has safety catches that will catch the lock gearing if it begins to fall. This can occur because of two possibilities, either the windlass has slipped off the spindle or the user has let go of the windlass. If the user has let go of the windlass, this can spin around rapidly and cause injury. The safety catches prevent this but only if used properly.

Slipping on wet surfaces – As with all British holidays, there is always the possibility of rain. Lock surfaces (mainly flat brick) can become very slippery when wet, especially as the users may not be focusing entirely on the task due to the weather.

Must have open access to the lock chamber – In an emergency, there must be at least one escape route from the inside of a lock chamber. If the lock chamber were to be fenced off, to prevent anyone from falling in, it would create a trap for those inside during use. The edges should be highlighted as much as possible.

Escape from an empty lock chamber – the sides may be many metres high. A ladder is required for the full height of the lock, set into the wall to allow for the boat to pass.

Swapping sides during use – This health and safety risk is especially pertinent for a single hander (a person who is cruising alone, so having to both drive the boat and work the locks at the same time). During the use of the lock, the lock gearing is situated on both sides of the locks, as are the balance beams for opening the locks. This means that the user frequently has to cross over narrow gates to gain access to the other side of the lock.

If possible, these risks should be eliminated or reduced by the proposed design changes.

Main Findings

The points below summarise the relevant information that has been gleaned from the engineering analysis of canal locks in the UK.

Gearing is important – There are two places where a human interacts with the lock: using the lock gearing and the balance beams. Whilst the human force experiment investigates the effect of the balance beams, there is no doubting the importance that the correct gearing makes on the ease of raising/lowering the paddles. As discussed previously, there are two main types of lock gearing currently in use – the traditional form, which counts for the majority of locks and the worm-gear mechanism. Hydraulic mechanisms for use in manually raising a lock paddle are in the process of being phased out.

The research results demonstrated that reasonable strength was required to initially move the bottom lock gate. The maximum initial force recorded was 245.25 N. This can easily be provided when opening a lock gate, as the user’s weight can be rested against the balance beam with ease. However, when generating the initial force to close a lock gate, the user’s weight can still be used but must be transferred through the user’s arms first.

The identification and calculation of the different forces affecting a gate as it is opened provided a surprising insight. The force of the water does not play a significant role in comparison to the other forces. In both cases, it was a similar result as to that of the inertia of the gate or beam. The equation created appears incomplete however, as the resulting force in the form of friction of the hinge seems unreasonably high. This implies that there is still an unidentified force in play, in addition to an accumulation of assumption and neglected elements, e.g. air resistance, etc.

Weight and material plays a large part in human force required – the weight of the gate and the buoyancy properties of the materials have played a large part of the force required to move it, as demonstrated when compared to the value of the results from the bottom gate (Lock 1) to the results from the top gate (Lock 3). The gate at Lock 3 was submerged in water and due to the smaller size (hence less weight) and the buoyancy properties of the oak, it took 91.89 N to move, whereas Lock 1, required an average force of 239.36 N.
A bywash angled at 90° to the boat can exact a force of 225.95 N on the hull of the boat, causing considerable difficult in maintaining a straight course. A bywash should be angled in the direction of flow to reduce this effect.

Water management plays a large part in cost maintenance - it accounts for a large portion of the cost of maintaining the canal system, costing approximately £890,000 in 2011.

Reviewing all of the analysis carried out in the above sections demonstrates that the use of canal locks have stood the test of time for a reason. They are very simple and easy to use – allowing use by families and new users alike.

However, there are certain elements that have been identified as possible areas for improvement: safety catches (pawls) in use on the lock gearing, opening mechanism, reduce water use, angle of bywash, use of turbine in paddle opening, modular design and materials of the gates.

Proposed Design Changes

Safety catches (pawls)

There are many different styles of catches on the lock system, with different purposes. The most basic, generally either an “o” shape or a “c” claw, are solely designed to hold the paddle at a certain height, using the tension caused in the chain to prevent the spindle from turning. A better designed safety catch is shown below in Figure 2. This type of catch has added protection that, if used properly, should the user drop their windlass, gravity pulls the catch down onto the cog and prevents the paddle from dropping. However, as shown, this design can be flicked off for the user’s ease and no longer offers protection. One proposal to resolve this is to add a small spring within the catch so that it no longer matters if it is pulled past the meridian.

Figure 2 - Standard safety catch (Powers, Standard safety catch [Photograph], 2013)

Opening mechanism

The use of lock mechanisms to open the paddles and balance beams to open the gates is remarkably simple to operate and effective, it does create the necessity to cross the lock several times in order to access each offside paddle and gate. In icy or wet conditions, the oak boards can be treacherously slippery. Whilst measures have been taken in the form of slip resistant coatings, if this need to cross from side to side could be eliminated it would reduce the risk of falling into the lock or canal significantly.
An option to consider would be to tie the opening of the paddles and the opening of the gates to the gearing mechanism. In this way, raising the pinion out of the top of

the gearing mechanism halfway would signal that the paddles are fully open. Once the lock is full, raising the lock gearing fully would then open the gate. This could all be completed from the towpath side of the lock and therefore eliminate any requirement for crossing over.

Reduce water use

Water loss will be reduced by the inclusion of small side ponds at each lock side. This means that only half the water will be lost by each lock ascent and descent. Leakage cannot be eradicated completely as materials wear but a tough flexible liner will be included on the ends of each area to provide as much protection as possible. When this wears, it can be replaced rather than having to change the whole gate.

Angle of bywash

As calculated in section *Force on boat hull from weir flow rate*, the force on a boat when bywashes are set at 90° to the canal can be up to 225.95 N. This can cause the boat to move sideways at a fair speed and should be prevented if possible. There are various ways to do this: changing the angle of the bywash so that it flows into the canal as close to parallel as possible, making use of baffles and also dropping the water from a height so that energy is dispersed in turbulence. This last option may cause unpredictable results however, when there is a large amount of water flowing through the bywash, emerging underneath the boat itself.

Use of turbine in paddle opening

Locks have been demonstrated as being quite costly in the form of electricity consumption for the water pumps. One idea to offset that cost is to install small water turbines in the opening of the paddle culverts. The maximum water velocity calculated in section '*Flow of water through a culvert'* was approximately 1.262 m/s. If the right size water turbine was selected, this water speed could be strong enough to generate electricity. The electricity generated from this can either be transferred directly to the nearest pump that is in use, or sold back to the grid (similar to small household generation sites) in order to create extra revenue for the Canal and River Trust. There would have to be precautions taken in terms of safety to users and protection to the wildlife, but it is a feasible concept.

Modular design

One of the quirks of the UK canal systems is that it was constructed by a variety of canal companies, who all had their own opinions as to how it should be constructed. One can recognise canal sections constructed by James Brindley, as he tended to make use of the contours in the landscape and construct lengthy stretches without the use of locks or boat lifts. In comparison, other canal builders opted for the use of a tunnel or a high number of locks to go over a hill and back down again, rather than wind around it. As the canals and waterways of the UK are now managed in the main part by one body, construction would be likely to take place in a very different way today. Canal sizes and therefore lock sizes would be standardised, which enables the use of a modular design rather than bespoke assemblies. This would not only reduce manufacturing costs but also enable more efficient maintenance.

Material selection

The material selection tool in the software CES Edupack 2012 was used to find materials that matched the following criteria in Table 8. These properties cover both the mechanical properties, processability of the material and the environmental properties, in the form of $C0_2$ production during the primary processing.

Properties	Value	Units
Max Price	1.65	GBP/kg
Max Density	7500	kg/m^3
Minimum Compressive Strength	300	MPa
Minimum Machinability	4	-
Durability to Fresh Water	Excellent only	-
Max $C0_2$ Footprint, Primary Production	100	Kg/kg

Table 7 - Selection parameters

Figure 3 - CES Edupack Results below shows the materials that meet the criteria – arranged in alphabetical order. It is worth noting that all of these are metals, whereas oak is the main material for gates currently.

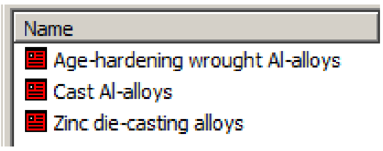

Figure 3 - CES Edupack Results

Of these materials, the prices are very similar, in the range of 1.46 – 1.67 GBP/kg. The two wrought aluminium alloys are more than half the density of the zinc die-casting alloys, making them more favourable from an inertia point of view. All have good machinability, allowing for low processing costs, and excellent resistance to corrosion from fresh water. The final consideration and one of the more crucial performance parameters is the fracture toughness. The materials in decreasing compressive strength are: age hardening wrought aluminium alloys (95 MPa – 610 MPa), zinc die-casting alloys (80 MPa – 450 MPa) and cast aluminium alloys (50 MPa -330 MPa). Age hardening wrought aluminium alloys would be the best selection as they are not only one of the cheapest (by a small margin), but they are also the lightest, yet has the strongest compression strength.

Conclusions

Throughout this article there have been examples of how work done in the 1800s by canal pioneers was a phenomenal feat. The aim of this article was to propose effective design changes to the UK's canal lock system and this was completed successfully via an in-depth engineering analysis and the design changes proposed to resolve the areas that were raised in the first section.

After a detailed analysis looking at elements such as water forces on stationary gates, flow dynamics through a culvert, forces on an opening gate and water usage – there were still only seven areas identified as an area of possible improvement.

The beauty of the locks is in its simplicity and accessibility and so with that in mind, those seven areas were developed into eleven design change proposals. The most significant is the removal of the balance beams and opening of lock gates using the paddle gearing. This eliminates the need to cross over the lock chamber at any point to operate the lock. Further elements which assist with ease of use are the fender boards and bywash design.

Whilst none of these changes can be called a 'major redesign', they would assist with ease of use, cut both running and maintenance costs and help the Canal and River Trust generate further revenue. This extra revenue could then be used to further develop canal or re-open disused lines allowing the expanding waterways tourist industry to go further than before.

Recommendations

This article has only really scratched the surface with regards to the engineering aspect of canal locks in the UK. Below are some options for further work to progress this investigation.

This article attempted to identify and calculate all the forces in effect on a lock gate, but had to neglect the effect of buoyancy as it was not within the article's scope. Further work could be undertaken to identify how buoyancy affects the amount of human work required to open and shut the gates. Work could also be undertaken to see how buoyancy affects the way the gates behave.

Whilst work has begun on identifying the forces of water through a paddle opening in a gate, further investigation could be undertaken to determine the feasibility of implementing a small water turbine in all lock culverts. This should include both gate openings and ground paddle culverts, bearing mind that there is a possibility of four gate paddles and four ground paddles at each lock.

This is an overview article and as such has provided several proposed design changes. Each of these suggestions need to undergo through a more rigorous and structured design process in order to determine the exact best way to address each possible areas of improvement.

This article has solely focused on the canal lock system in the United Kingdom, primarily England. There are much larger canal systems in place in the world, designed for sea going vessels. These also utilise locks but due to the size, many are electrically powered. Should the reader be interested, examples of locks on the Panama Canal are a good starting focus to investigate the use of locks on a larger scale.

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