Need for mechanical protection of Gabcikovo ship lock

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Abstract. The ship lock in Gabčíkovo has been for more than 20 years in operation, providing services for ships from many countries and nowadays is in an emergency state, when both chambers need to be closed because of damages on a gate and on structural parts of the lock chamber. Mechanical protection is the way how to increase its service life.

1. Introduction

Danube is the E80 trunk waterway connecting countries up to Black Sea. Gabčíkovo ship lock (Fig.1) with a hydroelectric dam feeder is located in a short distance from Slovak-Hungarian border and it has been operating from fall 1992. Lock chambers of the water structure Gabčíkovo are 275 meters long and 34 meters wide.

The feeder canal provides the water delivery to the turbines and a shipway into the Gabčíkovo ship lock chambers. The Shipping companies are organized by the Danube Commission and transportation of cargoes on the Danube is defined by Bratislava Accord, that evaluates one day of delay of the vessel of 1 300 deadweight tons for 430 Euros. A tugboat set may consist of several such vessels. An average number of tugs is about 20 per a lock/day. The costs for repair works only on a left lock, lasting four days, amounted 300 000 Euros. The ship lock has been providing services for ships from many countries and nowadays it is in an emergency state, when both chambers needed to be closed for a short period because of damages on a gate and structural parts of the lock chamber. The importance and construction costs for Gabčíkovo ship lock are enormous. In 2012, there were made 4063 fillings of the lock chambers and total of 13,767 vessels passed through. Since commencement of operation of the Gabčíkovo water structure a total of 318,176 vessels have passed through, which represents 122 901 099 tons of freight and 5 731 255 passengers.[1] When such amount of vessel float between the...
dams and ship lock walls many contacts happen between vessels and ship lock chamber walls and a dam blacktop revetment.

2. History

Hydro-electric plant with ship locks had been built from 1977 as an original hydro-electric plant Gabčíkovo-Nagymaros based on an international agreement aiming to prevent from regular (in 1954, 1965) floods in this area. In 1989, Hungary suspended the works on the Gabčíkovo – Nagymaros water structure system and despite a series of unsuccessful inter-governmental negotiations between 1990 and 1991, the Czechoslovak Government decided, mainly due to increasing economic and environmental losses, to start the operation of the Gabčíkovo water structure using a temporary solution known as the “C alternative”. The decision was speeded up also by an oil crisis in 1973. The hydro-electric plant was commissioned into operation in 1992. Recession from contract by Hungary had been for long years a subject of an international legal process between Slovakia (as an successor of liabilities after Czechoslovakia splitting-up) and Hungary. International Court of Justice decided in October 1997, that the international agreement from 1977 has been still valid.

The water structure system Gabčíkovo –Nagymaros consists of the following components:

- Hrušov – Dunakiliti weir at the Danube River kilometers 1,860 – 1,842(hereinafter referred to as “rkm”) with a maximum upper reach of 131.10 m above sea level on Slovak and Hungarian territory;
- Dunakiliti weir with an auxiliary ship-lock at rkm 1,842 on Hungarian territory;
- Derivation canal (intake and discharge canal) at rkm 1,842 – 1,811 on Slovak territory;
- Segment on the derivation canal on Slovak territory, consisting of a hydropower plant with an installed output of 720 MW, two lock chambers and facilities;
- Regulated old riverbed of the Danube at rkm 1,842–1,811 on the common Slovak-Hungarian section;
- Dredged and regulated old riverbed of the Danube at rkm 1 811 – 1 791 on the common Slovak-Hungarian section.

3. Ship lock operation

Lock mooring is a commonly used method of navigating into a lock by a barge travelling upstream.(Fig. 3) The barge would be directed to the slack water to one side of the lock gates and as the volume of water decreased as the lock emptied the barge or boat is effectively sucked out of the slack water into the path of the lock gates. The effort required to navigate the barge or boat into the mouth of the lock is therefore substantially reduced. Ship lock chamber is a place, where the ships sailing on the Danube river pass through a weir. There are two chambers in Gabčíkovo; their depth is approximately 32 meters. A vessel floating down-the-river enters into a chamber), then a part of water is drained from a weir and a vessel continues in shipping. It takes about 15 minutes. The water flows into, or on contrary, flows out through orifices in the bottom. An exploitable length of each ship lock chamber is 275 meters and width of 34 meters that is more than in the Panama Canal.

Fig.3 Vessels waiting in a chamber
4. Damages on a feeder canal and shiplock chambers.

Only the most experienced captains are allowed to operate a vessel within the ship lock chamber. Nevertheless, recently a number of accidents in the chambers has increased. Despite the fact of its great importance, the ship lock has not been protected against any irresponsible and inexperienced captains causing damages on the ship locks structure by hitting with vessels to the walls and gates of the ship lock. The hits on walls of the chamber or on the gate supports are not sporadic and a subsequent investigation of an offending personnel or organization does not bring satisfactory results. Even water police is unable to prevent hitting the wall of a chamber. From a classification of damages on a feeder canal and its asphalt-concrete isolator there are horizontal and vertical cracks over the water level and asphalt leaked out mainly in a transition curve between a water-side slope and a dam crest. Under the minimum operational water level the dents were found caused by impacts of vessels floating in a feeder canal (Fig. 5) The only way that is able to reduce inevitable damages resulting from hits is mechanical protection of the chamber as well as of the vessels entering into a ship lock chamber. An increased number of non-convenient and non-competent shipping and vessel leadership has resulted in repeated damage of the upper support of the lock gate. The company carried out regular repairs and maintenance of specific water structures as well as repairs of damaged technical equipment. In 2012, the VV Inc. Company, repaired right lock chamber on the water structure Gabčíkovo (Fig. 6.) Total debt rate of the Gabčíkovo ship lock operator is almost 39%, so the new investments are not feasible. The Gabčíkovo ship locks are similar to Panama locks with respect to technical features, however Panama locks have been operating for more than 80 years and they are still in excellent conditions.

5. Calculation of fenders capacity

The principal function of the fender system is to prevent the vessel or the dock from being damaged during the mooring process or during the berthing periods. Forces during the vessel berthing may be in the form of impact, abrasive action from vessels, or direct pressure. These forces may cause an extensive damage to the ship and structure if suitable means are not employed to counteract them. The amount of energy absorbed and the maximum impact force imparted are the primary criteria applied in accepted fender design practices.
A variety of factors affect the proper selection of a fender system. These include, but not limited to, local shipping environment, class and configuration of ships, speed and direction of approach of ships when berthing, available docking assistance, type of berthing structure, and even the skills of pilots or ship captains. It is considered impractical to standardize fender designs since berthing conditions are rarely identical.

In boating, a fender is a bumper used to absorb the kinetic energy of a boat or vessel berthing against a jetty, ship lock wall or other vessel. To prevent the vessels from damage, fenders usually have high energy absorption and low reaction force. Fenders are typically manufactured out of rubber, foam or plastic. Their absorption features are compared in the Figure 7. Rubber fenders are either extruded or made in a mould. Designing a fender system basically is determining what the berthing energy of a vessel or range of vessels will be, and then determine what capacity the fender needs to have to absorb that kinetic energy and finally how to find a way to avoid the reaction force creating too much hull pressure. Composites have dramatically higher specific energy absorption than steel or aluminum. Composite-based crush cones and similar structures built into berthing wall can absorb 120 kJ/kg, even up to 240, vs. about 20 for steel. Crush properties and costs can also be optimized by mixing costlier carbon fiber with lower-cost materials like fiberglass.

6. Calculation of berthing energy
The method to define kinetic energy can be used in the determination of berthing energy of the ship. Work is closely related to energy

\[ W = F \cdot s \]  \hspace{1cm} (1)

if a force of 10 Newtons (F = 10 N) acts along a point that travels 1 metres (s = 1 m), then it does the work \( W = (10 \text{ N})(1 \text{ m}) = 10 \text{ N m} = 10 \text{ J} \). Transferred into tons and km the above mentioned is equal to

\[ 10 \times 10^{-3} \text{ ton} \times 1 \times 10^{-3} \text{ km} = 10 \text{ J} \]

The kinetic energy method has been the widely accepted method for piers, wharves and ship lock facilities. When the tonnage of the ship is known, the energy equation can be written as:

\[ E_{\text{ship}} = F \cdot s = \frac{1}{2}mv^2 \]  \hspace{1cm} (2)

where \( E_{\text{ship}} = \) Berthing energy of ship (MJ)
\( m = \) weight of the ship in tons
\( v = \) Berthing velocity normal to the berth (km/hour = 0.278 x 10^{-3} \text{ km/s} ), speed of the center of mass of the vessel body.

Since the kinetic energy increases with the square of the speed, an object doubling its speed has four times as much kinetic energy.
The kinetic energy of a vessel is related to its momentum by the equation

\[ E_k = \frac{p^2}{2m} \]  \hspace{1cm} (3)
p- is momentum
m – is mass of the vessel

The kinetic energy of such systems depends on the choice of reference frame: the reference frame that gives the minimum value of that energy is the center of momentum frame, i.e. the reference frame in which the total momentum of the system is zero. This minimum kinetic energy contributes to the invariant mass of the system as a whole.

In principle, a berthing energy calculation is a simple kinetic energy calculation, adjusted for specific behavior of a berthing vessel or the specific characteristics of the berthing location or structure. The time-dependent motions of the ship shall be studied using the coordinate system seen in Figure 8, where xb, yb, zb are the coordinates relative to the center of gravity of the ship G; xo, yo, zo are the global coordinates relative to a point S in the space, where S is on the free surface of otherwise calm water; and x, y, z are the ship-fixed coordinate system relative to the center of gravity of the ship G, moving together with the ship. The angular motions of the ship shall be relative to those three axes: roll, pitch, or yaw.

The work done accelerating a particle during the infinitesimal time interval dt is given by the dot product of force and displacement:

\[ F \cdot dx = F \cdot v \, dt \]

where we have assumed the relationship \( p = m \cdot v \).

Applying the product rule we see that:

\[ d(v \cdot v) = (dv) \cdot v + v \cdot (dv) = 2 \cdot (v \cdot dv) \]

Therefore (assuming constant mass so that \( dm = 0 \)), the following can be seen:

\[ v \cdot d(mv) = \frac{m}{2} \, d(v \cdot v) = \frac{m}{2} \, d \left( \frac{mv^2}{2} \right) \]

Since this is a total differential (that is, it only depends on the final state, not how the particle got there), we can integrate it and call the result kinetic energy. Assuming the object was at rest at time 0, we integrate from time 0 to time t because the work done by the force to bring the object from rest to velocity v is equal to the work necessary to do the reverse:

\[ E_k = \int_0^t F \cdot dx = \int_0^t v \cdot d(mv) = \int_0^t d \left( \frac{mv^2}{2} \right) = \frac{mv^2}{2} \]

The abovementioned relations were applied during calculations of kinetic energy produced by the types of vessels commonly operated on the Danube river: DNL2000, KVC1000, UC1500 (Fig.9), DE1600, VC850, Ro-ro at angles 5,10,15,20,25,30,35,40 and 45 degrees and velocity of berthing operation from 0,1 up to 5,0 km/h and their combinations. (Fig.10)
However there are several factors that modify the actual energy to be absorbed by the fender system. The energy absorbed by the ship depends on the relative stiffness of the ship and the obstruction. The deformation coefficient varies from 0.9 for a non-resilient fender to nearly 1.0 for a flexible fender. For larger ships on energy-absorbing fender systems, little or no deformation of the ship takes place; therefore, a coefficient of 1.0 is recommended. Configuration Coefficient (Cc) is implied when the water between the berthing ship and the structure is squeezed, which introduces a cushion effect that represents an extra force on the ship away from the berth and reduces the energy to be absorbed by the fender system. Experience has indicated that for a solid quay wall about one quarter of the energy of the berthing ship is absorbed by the water cushion. For berths with different conditions, Cc might be chosen somewhere between these values 0.8-1.0.

When a ship approaches a dock, the berthing impact is induced not only by the mass of the moving ship, but also by the water mass moving along with the ship. The latter is generally called the "hydrodynamic" or "added" mass. In determining the kinetic energy of a berthing ship, the effective or virtual mass (a sum of ship mass and hydrodynamic mass) should be used. The hydrodynamic mass does not necessarily vary with the mass of the ship, but is closely related to the projected area of the ship at right angles to the direction of motion. Other factors, such as the form of ship, water depth, berthing velocity, and acceleration and deceleration of the ship, will have some effect on the hydrodynamic mass.

7. Measures to reduce the damages on a ship lock

Various kinds of measures (Table 1) can reduce the unfavourable effects of the environment and forces having impact on the vessel in the chamber. There are many factors having an influence on the situation in the chamber, namely experience of the captain, size of a vessel, speed of filling in, speed of emptying the chamber, water regime, speed of water current, speed of a vessel, composition of vessels formation, day or night time, visibility conditions, availability of a port tug with a navigating personnel, training of personnel, competence, staffing of vessel crews, level of
responsibility and liability for damages, and the last but not the least discipline of captains, their nationality, different national shipping regulations and legal regulations. These measures differ in fund and time demandingness.

Table 1. Investments in mechanical protective measures aiming to reduce damages

<table>
<thead>
<tr>
<th>Protected object</th>
<th>Investments</th>
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<tbody>
<tr>
<td></td>
<td>Long-term investments</td>
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<tr>
<td></td>
<td>-higher quality of material used during vessel construction</td>
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<td></td>
<td>-tug fenders</td>
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<tr>
<td>vessel</td>
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<tr>
<td>Ship lock chamber</td>
<td>- Higher quality of material used during ship lock construction, - length of an intake and discharge canal,</td>
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<tr>
<td></td>
<td>- mooring equipment for vessels</td>
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<tr>
<td></td>
<td>- permanent fenders on lock walls</td>
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<tr>
<td></td>
<td>- mooring equipment for vessels waiting for a ship lock chamber</td>
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</table>

7.1. Wooden fender

As far back in the history common people knew that wooden pieces effectively damp an impact force. In general the wood fenders were fitted to gates in places where they might be hit by vessels. In the case of miter gates they are recommended to be fitted with wood fender.

![Fig.12 Wooden fender on a ship and a lock wall](image)

on the outside surface of the opened gates to protect the construction from damage caused by inbound and outbound vessels.
However all loosen objects, which fall down into water and get in between the gates, may destroy the gate, therefore permanently installed or fixed and movable fenders on a chain are preferred.

7.2 Truck tire fender
The simplest and the less expensive way how to protect both chamber wall and a vessel is a truck tire.

![Fig.13 Tires protecting a wall from a vessel impact](image13)
![Fig. 14 Roller fender](image14)

Roller fenders are usually installed to guide ships in restricted spaces like walls of locks and docks. They can also be used on corners and lock entrances where lower energies are needed. Features of a roller fender include good energy absorption, gentle contact face, low rolling resistance, use singly or in multiple stacks, composite and stainless steel bearings, low maintenance frame design. Roller fenders use stainless steel and composite bearings which give a very low rolling resistance and require virtually zero maintenance. Wheel fenders are widely used on environments with exposed corners to help ships maneuver into berths and narrow channels such as locks and dry-dock entrances. The main axle slides on bearings and the wheel reacts against back rollers to provide high energy and minimal rolling resistance, whilst the stainless steel and composite bearings are almost zero maintenance.

7.3 Foam fenders
In order to enable safe ship-to-ship and ship-to-quay berthing operations and meet the most stringent quality and performance demands the manufactures produce foam fenders as an alternative to the standard pneumatic fenders and shock absorbers. Foam fenders, all share the same manufacturing technology centered on an outer reinforced skin. Foam fenders absorbs the impacts whilst the skin resists wear and tear in use in any tough conditions, thus providing tough, heavy-duty fendering systems for harbors, offshore and
ship-to-ship applications. The key attributes of the foam fenders include high energy absorption and low reaction force, a foam fender conforms to hull protrusions, it has an ultra-tough, unsinkable design, it remains fully functional even if skin is punctured and requires low maintenance and an easy installation.\[5\]

7.4. Prevention from damage on a vessel hull

Design of all fender systems is to prevent permanent deformation of the ship's hull. It is much more expensive to repair a ship's hull than rehabilitate a damaged fender system. The composition of a typical river ship hull is steel plating welded to longitudinal (horizontal) stiffeners at 0.6 to 1.2 m on center. The stiffeners span from 1.5 to 7.6 m depending on the vessel. Generally, the stiffeners are of sufficient strength to preclude failure from fender loading. However, the hull plating may yield when subjected to a uniformly distributed overload on the panel. Fender systems with rigid face elements or in combination with rigid camels tend to concentrate the reaction forces on the ships frames versus the hull plating due to the relative stiffness of the frames.

Tug fenders must work harder, for longer and under more extreme conditions than any other fender type. Tugs may be fitted with up to four types of fender – each type serving a particular application. As many tugs become more powerful, some exceeding 100t bollard pull, choosing the right type, size and arrangement of fenders becomes critical. Cylindrical tug fenders are fitted to the bow/stern of tugs and usually used to push against flared hulls and in open river conditions. Large cylindrical fenders are often used as the primary pushing fenders on the bow or stern of modern tugs. Their round shape is ideal for working with large bow flares (like container ships), but are equally good for pushing flat-sided vessels. Tug cylindrical come in diameters to 1000 mm and in very long continuous or spigot-joined lengths. A longitudinal chain runs down the centre of the fender, supplemented by circumferential straps or chains which are recessed into grooves. Tapered ends are also available.

7.5. Pneumatic fenders

Floating pneumatic fenders with chain and truck tire net or tire netting. The pneumatic fender of the net with chain and tire protects the fender body from damaged by sharp objects, the net also via the absorption of sheer loads during berthing. The better the pneumatic fender net, the more protection it will offer.

8. Preservative Treatment.

All timber members, with the exception of some fender piling, exposed to the water and air environment and immersed in water should be pressure treated with oilborne (creosote, pentachlorophenol) or waterborne
chemical preservatives to protect against deleterious effects of decay, insects, and borers. If possible, pressure treatment after all holes and cuts are made. When holes and cuts are made in the field, timber members with preservative should be treated to prevent decay from starting in the holes or cuts.

Therefore, whenever possible, design and detailing should avoid the necessity for making cuts or holes on underwater timber members. For example, avoid bracing or connections below mean high water are to be avoided.

9. Conclusion

The practice has shown that no protection of estates is the worst behavior of the owner, should it be anyone, a natural person, joint-stock company or a state organization. The Gabčíkovo water structure was built in hard economic and political conditions when Slovakia has taken over all responsibility for its completion and operation. Even the previous generations knew how to protect such huge water structures. An excuse for non-protecting the water structure due to lack of funds does not work at all, as many protective measures need no funds. Old truck tires protect the ship lock chamber in the same way as a hull of a vessel. Very rough calculation of economical consequences resulted from negligence to irresponsibility and incompetency of some vessel captains is breath-taking.

The Gabčíkovo water structure brings only benefits and nowadays great incomes, so it should be protected by all available means, including the mechanical ones.

References


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