Boat Lift for Orlík Dam

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Abstrakt

Článek pojednává o koncepčním návrhu zdvihadla s použitím protizávaží pro přehradu Orlík. Jsou zde uvedeny výpočty hlavního lanového pohonu a konstrukční návrh řešení pohonu. Také jsou zmíněny některé možné problémy týkající se vlastní realizace a konstrukční principy týkající se detailního návrhu některých prvků zdvihadla.

Klíčová slova

Lodní zdvihadlo, koncepční návrh, aplikace protizávaží, lanový pohon

1. Introduction

The river Vltava was used by people for centuries, especially for transport of different goods and later for producing electricity. There was endeavour to improve navigability in connection with the utilization of the river and enable vessels to use the river along the possible length. During the 20th century, especially in 1950s, Vltava cascade which is constituted by a system of 9 dams was built, so the energetic purpose of the river came into focus. Other important impact connected with the cascade of dams must be mentioned, firstly accumulative function and therefore regulation of the flow downstream the river Vltava or Labe. Side but very important effects of the accumulative function of the dams are protection against flood, improvement of navigability of some parts of the river, stabilization of water level for water intake and new recreational places were arisen. On the other hand building of the dams was accompanied by negative consequences such as disappearance and destruction of some outstanding historical or natural locations and traditions.

1.1 Navigability of Rivers

Although the cascade of dams represents certain obstacle for vessels to overcome, some principles how to solve it may be found. One of them is a system of lock chambers, other solution are so called boat lifts. Main purpose of these facilities is to overcome a slope of river, the vertical difference of water levels. We can find different types of boat lifts in many countries, basic classification of boat lifts may be devided into three groups: vertical, inclined plane and others. Examples of different types of boat lifts with the realization are shown in fig. 1, fig. 2 and fig. 3, lock chamber is shown in the fig. 4. Most of boat lifts operated in these days use the principle of the cage filled with water so the weight of elevated burden is constant. The cage is connected to a counterweight with a system of cables to reach the equilibrium of the system. Therefore the drive of the whole system can have less power because it compensates losses in the mechanism caused by friction.

Fig. 1. *Vertical boat lift in Strépy-Thieu*

Fig. 2. *Inclined plane boat lift in Marne-Rhine Canal*

Fig. 3. *Rotational boat lift Falkirk Wheel*

Fig. 4. *Lock chamber*

Each solution is characterized by its own advantages and disadvantages. If we focus on the differences between lock lifts and chambers, high elevation on the relatively short distance is achieved by a boat lift in comparison to lock chambers when more steps are needed. Also the water consumption or energy consumption thanks to counterweights of boat lifts are not so significant. However, there are some limitations of boat lifts that diminish their frequent utilization. For example difficulty designing or changing parameters of the boat lift, investment intensity and limited transport capacity must be mentioned.

1.2 Historical Development

Historically, building of boat lifts was considered during the realization of Danube-Oder-Elbe water corridor at the beginning of 20th century. At the present time there are two possible locations in Czech Republic where the technical realization of a boat lift is feasible and tentatively scheduled. Both locations are on the above mentioned Vltava cascade of dams, one location is Slapy dam, the other is Orlík dam. Structures of the dams are partly arranged for the project of a boat lift, these structures were built during the realization of the dams in the middle of 20th century and some of them might be used for the future boat lifts. Original conception of the vertical boat lift on the Slapy dam was planed therefore some structural adaptations of the dam were prepared.

Many drafts of the boat lift solutions on the Orlík dam were proposed, example of original conceptual design should be apparent from the figure 5 (see reference [1]), where the design of the boat lift by Záruba is presented. This solution takes advantage of a counterweight which results in effective operating costs reduction, simplification of track loading and concentration of loading into an exactly specified part of the dam construction. Therefore drafts of the solution discussed below in this text uses counterweight for balancing the cage with the vessel.
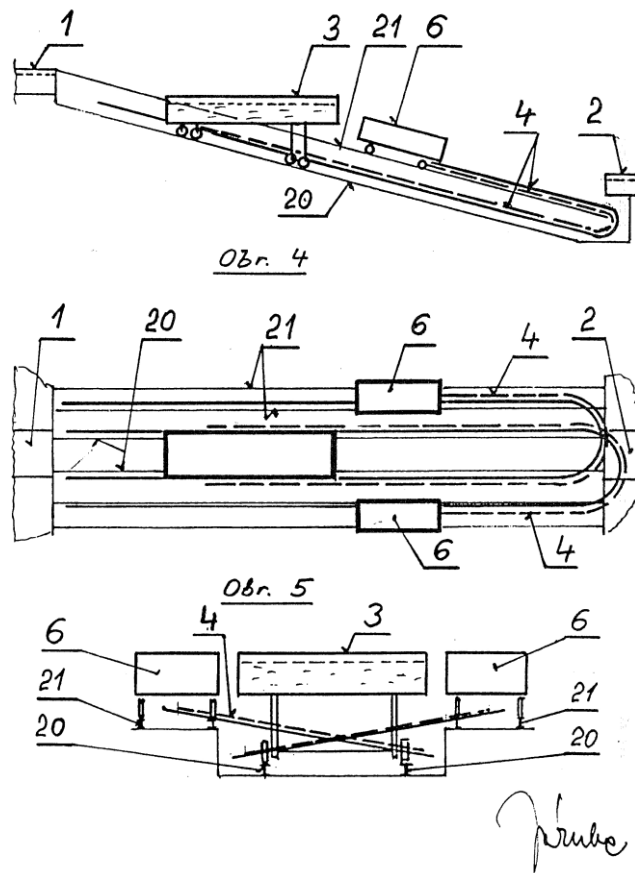
Fig. 5. Boat lift design by Záruba on the Orlík dam

Present state of the construction and location of the boat lift on the Orlík dam are shown in the figures 6 and 7.

Fig. 6. Orlík dam

Fig. 7. Track for the boat lift

2. Boat Lift Calculation

In general, the operation of the boat lift can be characterized by five basic operating states:

1. steady drive of the cage upwards
2. steady drive of the cage downwards
3. immersing of the cage into the water in the lower station
4. emerging of the cage from the water in the lower station
5. steady drive of the empty cage (winterize of the boat lift)

The operating states 1, 2 and 5 can be described as a state when the system is balanced by the counterweights. The state 5, the tank is without water, is balanced by means of release of some carriages with counterweights when the unused section of the counterweight assembly is parked in the suitable position of the track. The operating states 3 and 4 complicate the cycle of the lift by reason of unbalanced system given by variable lift force of water.

The conceptual design of the drive should be clear from the figure 8. The traction cables are pulled by two winches, assemblies of driving pulleys that are 5.9 metre in diameter and guided by pulleys that are 4 m in diameter. Each of two driving mechanism is driven by an induction motor and revolutions of the motor are reduced by a planetary gearbox. The counterweight consists of two assemblies of 6 carriages ballasted with cast iron blocks.
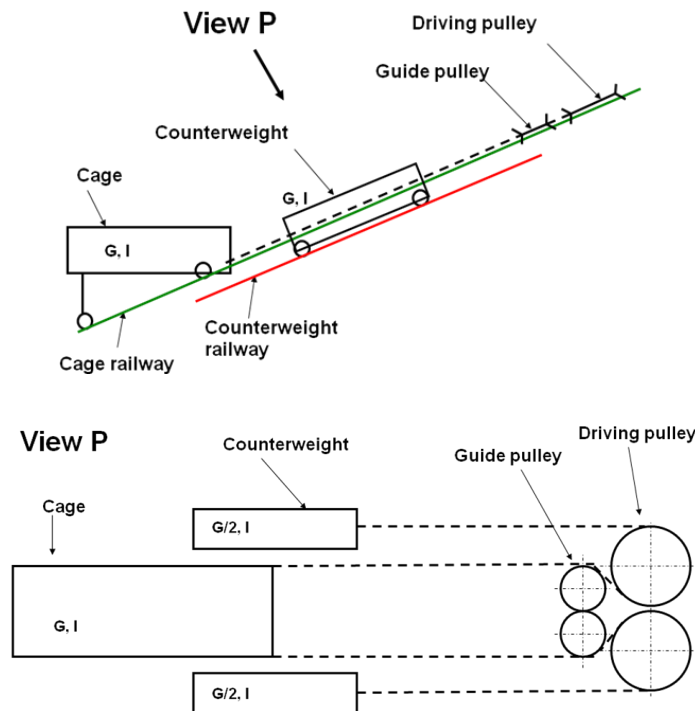

Fig. 8. *Conceptual design of the boat lift*

Calculations of driving force and operating power for each state were performed according to the schemes in figures 9 - 12. If we consider input parameters given in table 1, the result values calculated according to equations (1) – (8) are summarized in table 2.

Table 1. *– Input parameters for calculation*

G_c	11 075 kN	total weight (cage + water + vessel)
G_{ocel} - V_c	4 664 kN	total weight during immersing and emerging of the cage
Z	11 075 kN	weight of the counterweight
w_p	0,016	drag coefficient
η_F	1	mechanical efficiency of the cage mechanism
η_Z	1	mechanical efficiency of the counterweight mechanism
η_1	0,98	mechanical efficiency of the cable drive mechanism
v	0,2 m/s	stable speed
	0,04 m/s	speed during immersing and emerging of the cage
α	22°	angle of inclination

Table 2. – *Calculated values of the operating states*

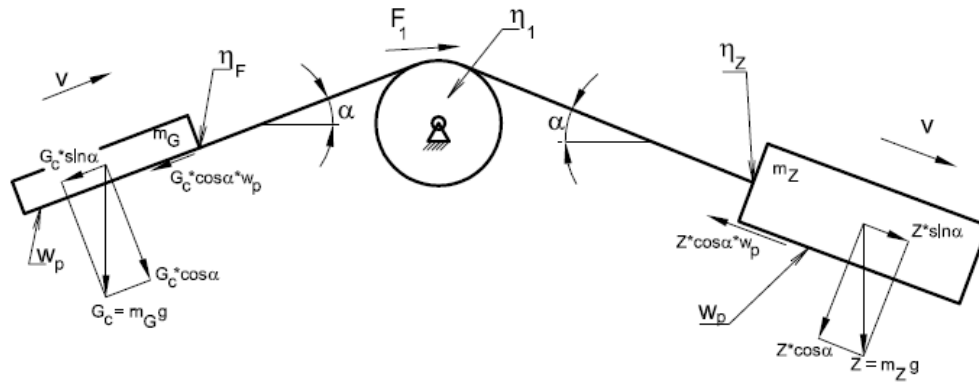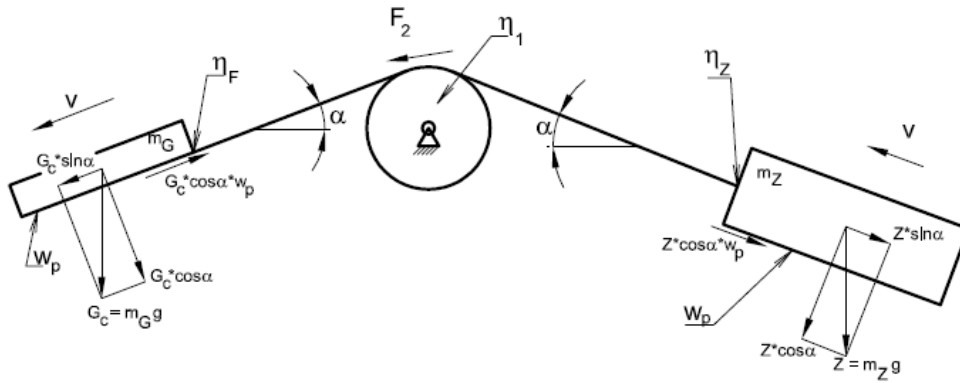| Operating state	Driving force	Calculated power
(1) steady drive of the cage upwards	417 kN	83 kW
(2) steady drive of the cage downwards	408 kN	82 kW
(3) immersing of the cage	2669 kN	107 kW
(4) emerging of the cage	2131 kN	85 kW

Fig. 9. *Computational schemes – operating state 1*

$$F_1 = G_c \cdot (\sin\alpha + w_p \cdot \cos\alpha) \cdot \frac{1}{\eta_F \cdot \eta_Z \cdot \eta_1} - Z \cdot (\sin\alpha - w_p \cdot \cos\alpha) \tag{1}$$

$$P_1 = F_1 \cdot v \tag{2}$$

Fig. 10. *Computational schemes – operating state 2*

$$F_2 = -G_c \cdot (\sin\alpha - w_p \cdot \cos\alpha) \cdot \frac{1}{\eta_F \cdot \eta_Z \cdot \eta_1} + Z \cdot (\sin\alpha + w_p \cdot \cos\alpha) \tag{3}$$
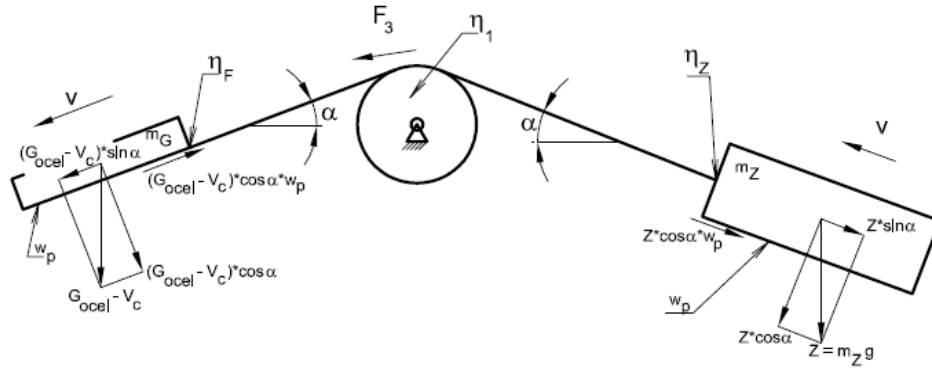
$$P_2 = F_2 \cdot v \tag{4}$$

Fig. 11. Computational schemes – operating state 3

$$F_3 = -(G_{ocel} - V_C) \cdot (\sin\alpha - w_p \cdot \cos\alpha) \cdot \frac{1}{\eta_F \cdot \eta_Z \cdot \eta_1} + Z \cdot (\sin\alpha + w_p \cdot \cos\alpha) \qquad (5)$$
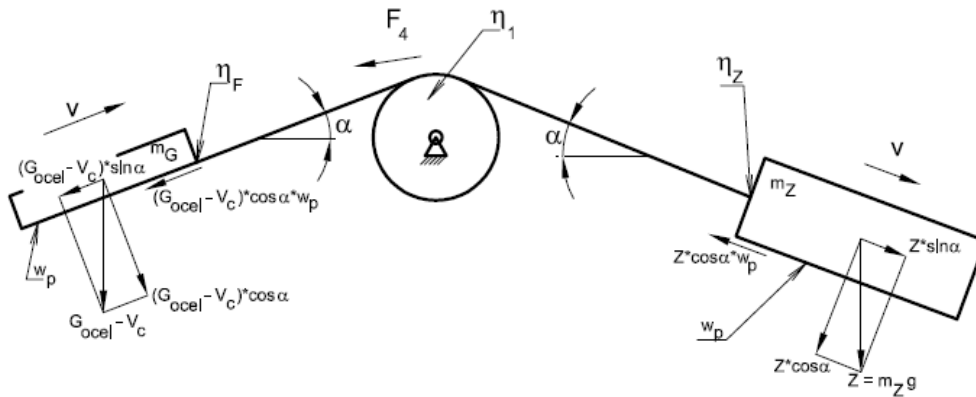
$$P_3 = F_3 \cdot v \qquad (6)$$

Fig. 12. Computational schemes – operating state 4

$$F_4 = -(G_{ocel} - V_C) \cdot (\sin\alpha + w_p \cdot \cos\alpha) \cdot \frac{1}{\eta_F \cdot \eta_Z \cdot \eta_1} + Z \cdot (\sin\alpha - w_p \cdot \cos\alpha) \qquad (7)$$

$$P_4 = F_4 \cdot v \qquad (8)$$

3. Boat Lift Details Design

There are many details of the boat lift that are supposed to be designed before the realization is started. Some of crucial ones are described below together with possible solution.

3.1 Upper station

Crucial problem of the boat lifts planned on the Orlík dam is the fact that the river Vltava is used as a water resource and for electric power generation. Hence, the water level in upper and lower end station is not constant but it changes depending on a season and actual water consumption of power plant. In consequence of this fact the optimal structural design in the end stations was chosen, so the cage will immerse into the water in the lower end station. Structural designs of the upper end station were more complicated, the main idea is based on the application of a sealing element that is movable together with the cage or adjustable according to the actual water level. Some examples of the drafts and detailed designs are shown, e.g. the figure 13 illustrates the structural design of sealing plate with a pneumatic sealing connected to the cage.
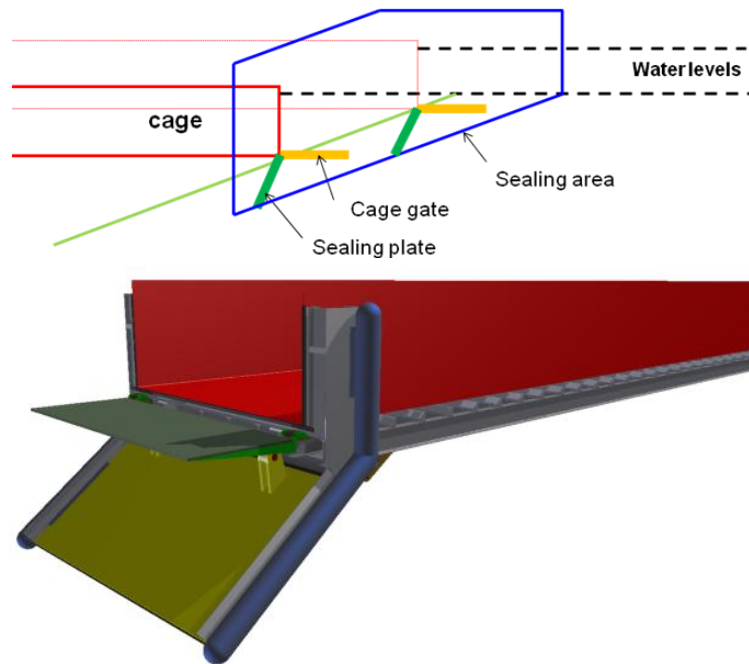
Fig. 13. *Upper station – sealing plate*

Another solution of the upper station uses sealing shield that is adjusted based on the actual water level, see figure 14 with the basic draft and detailed final design. The cage of the lift boat arrives to the position that is variable and depends on the water level, then the cage is sealed to the sealing shield, finally gates of the cage and sealing shield are opened. The design shown in the figure uses counterweight for elimination of hydraulic pressure on the shield and for reduction of required power of the driving mechanism that moves the shield.
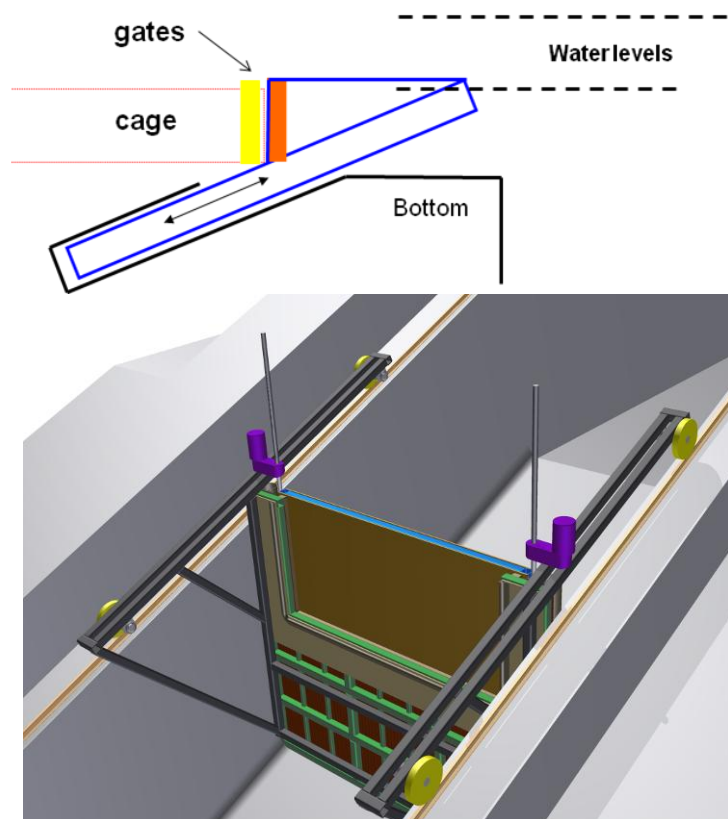

Fig. 14. *Upper station – sealing shield*

3.2 Drive mechanism

Drive mechanism is one of the essential parts of the boat lift and the conceptual design should be apparent in the figure 15. Total number of 16 cables 50 mm in diameter were proposed according to safety, therefore each hoist is compound of eight driving and eight guiding pulleys. The assembly of the pulleys can be designed as a compact hoisting drum or as a system of independent pulleys. The dimensions of the drive mechanism, pulleys and cables are designed considering minimal intensity of bending stress of cables, minimal wear of driving pulleys, optimal utilization of space for the mechanism and sufficient angle of contact between pulley and cable.
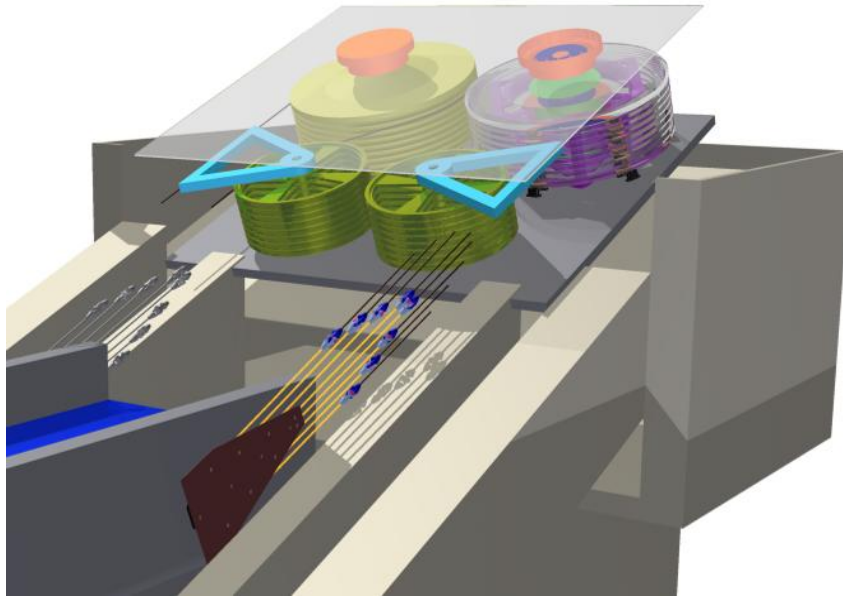

***Fig. 15.** Drive mechanism*

If we consider operating speed of the boat lift 0.2 m/s, diameter of driving pulleys 5.9 m, an induction motor with 1450 rpm, there has to be a reduction gearbox with reduction ratio 2240 to achieve output speed of the driving pulley 0.65 rpm. Possible configuration of the drive mechanism is shown in figure 16. The induction motor performance for one driving unit is set according to calculated power for each operating state. Provided that the required power for compensating mechanical losses in operating states 1 and 2 is approximately 90 kW, the total performance is set to 150 kW, i.e. 75 kW for each driving unit. System of driving for other operating states 3 and 4 has to be realized in other way – see text below.
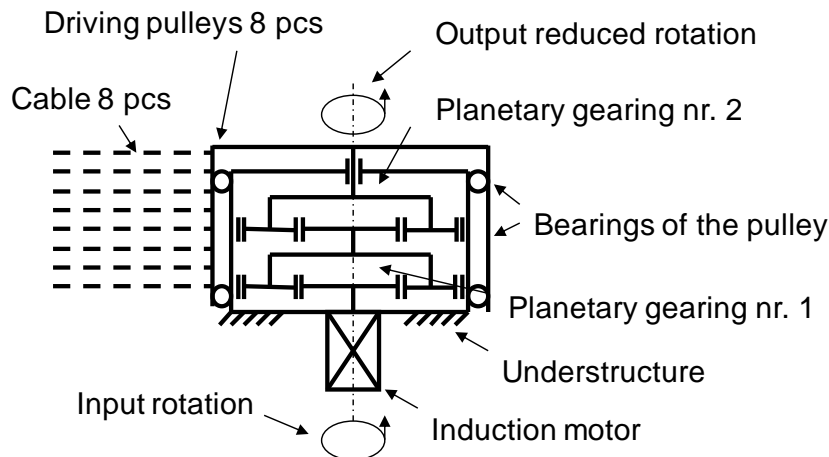

***Fig. 16.** Configuration of the drive mechanism*

Let us focus on the force transmission on the pulley and use equation modelling belt friction (9). If we assume the coefficient of friction f = 0.1 and achieved angle of contact φ = 229°, based on the equation (9) we get possible ratio $T_1 / T_2 = e^{\varphi f} = 1.49$. If force $G_c \cdot \sin\alpha$ is a preload on the both ends of a cable and F is a force that must act on the one end of cable to exceed passive resistance for each operating state, then we can determine ratio T_1 / T_2 for each operating state and subsequent safety towards the $e^{\varphi f} = 1.49$, which is attainable on the hoist – see equation (10). The result values are summarized in table 3.

$$\frac{T_1}{T_2} = \frac{G_c \cdot \sin\alpha + F}{G_c \cdot \sin\alpha} = e^{\varphi f} \qquad (9)$$

$$k = \frac{1.49}{\dfrac{G_c \cdot \sin\alpha + F}{G_c \cdot \sin\alpha}} \qquad (10)$$

Table 3. – *Safety on the hoist for operating states*

Operating state	(1)	(2)	(3)	(4)
F [kN]	417	408	2669	2131
T_1 / T_2	1.100	1.098	1.643	1.514
k	1.354	1.356	0.90665	0.98432

We can see from the results in table 3 that operating states 1 and 2 can be safely driven using designed driving mechanism with hoist, other operating states 3 and 4 must be driven by another mechanism. One example of such driving mechanism is drafted in the figure 17, when the carriages of a counterweight are driven using a rack and a driving wheel.
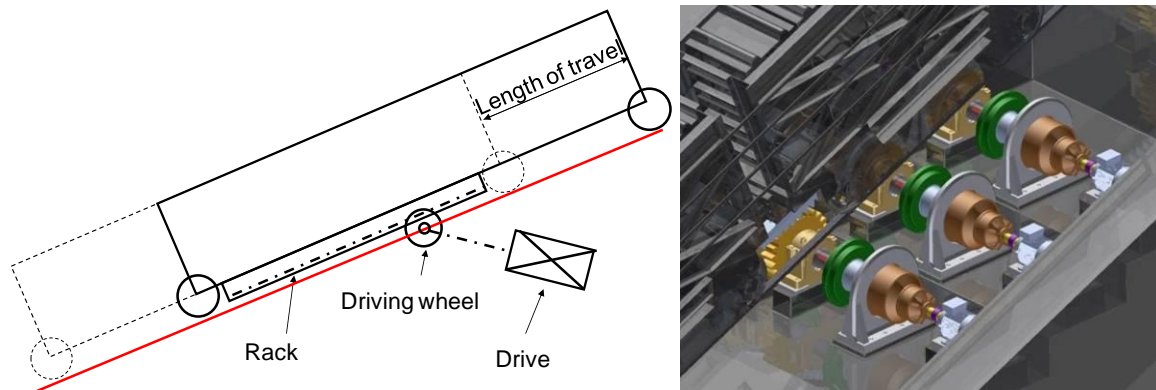

Fig. 17. *Driving mechanism for operating states 3 and 4*

3.3 Counterweight

The boat lift is supposed to be out of order during winter. Therefore the empty cage without water is planed to be winterized in the upper station. The easiest and most suitable way how to empty the cage is not to close the gate in the lower station and pull the cage upward. However, the empty cage unbalances the whole system, so the part of the counterweight must be disconnected, parked and fixed in the upper station, the rest of the counterweight correspond to the empty cage. Possible solution of the counterweight is composed of carriages ballasted with cast iron blocks, one carriage for guiding cables and one carriage for hydraulic attachment of cables – see figure 18.
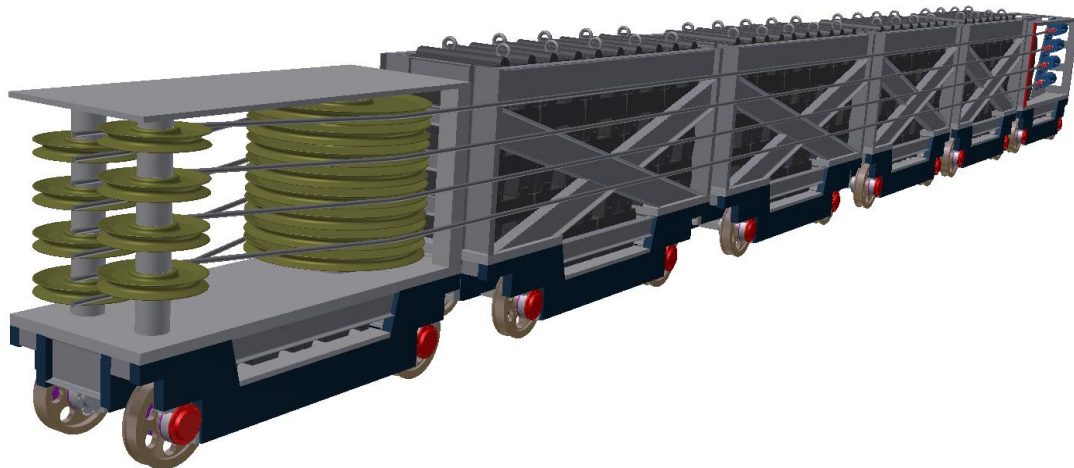
Fig. 18. *Counterweight*

5. Conclusion

Conceptual design and calculations of the boat lift on the Orlík dam represent the opportunity how to achieve the navigability of the river Vltava. The study shows and solves the principle using counterweight that is suitable to reduce operating costs. Also the draft of a drive mechanism whose power parameters for each operating state were calculated is designed and presented. Further detailed design of the boat lift and all components is needed in case of the continuation of the project. Possible problems and principles mentioned in the text must be considered as well.

List of Symbols

G_c	total weight (cage + water + vessel)	[kg]
$G_{ocel} - V_c$	total weight during immersing and emerging of the cage	[kg]
Z	weight of the counterweight	[kg]
w_p	drag coefficient	[-]
η_F	mechanical efficiency of the cage mechanism	[-]
η_Z	mechanical efficiency of the counterweight mechanism	[-]
η_l	mechanical efficiency of the cable mechanism	[-]
v	speed of the cage	[m/s]
α	angle of inclination	[°]
F	driving force	[N]
P	calculated power for operating states	[W]
f	coefficient of friction	[-]
φ	angle of contact	[°]
T_1, T_2	force in cables	[N]
k	safety factor	[-]

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