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Planning of the ship lift at the Three Gorges dam in China

A vertical ship lift based on the counterweight principle is to be built to allow passenger ships to pass the Three Gorges Dam at the Yangtze River near Yichang. This project is being realized by the China Yangtze Three Gorges Project Corporation, building and operating company of the Three Gorges Dam. The German joint venture, "German Design Group", incorporating the two companies Krebs und Kiefer International and Lahmeyer International has been entrusted with the general layout, intermediate and final design. As part of the "Panel of Experts" the German Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute) provides consulting support to the building company.

1 Introduction

China's objectives in the Three Gorges Dam project on the Yangtze River are to generate electrical energy, to protect densely populated areas from flooding and to improve conditions for navigation on the river.

The dam is a concrete gravity dam 2310 m long and ca. 180 m high. The stretch of river behind the dam is ca. 660 km long, so that a flood reservoir capacity of 22,15 billion m³ will be created. The power station, which has 26 Francis turbines each with 700 MW installed capacity, will generate ca. 85 TWh of electricity per year. To allow ships to overcome the height difference of 113 m, there is a two-lane chain of locks consisting of five lock chambers with effective dimensions of 280 m length, 34 m width and 5 m depth of water each, and in future there will also be a vertical ship lift based on the counterweight principle (Figure 1).

As a result of the construction of the dam, the Yangtze, the longest river in Asia, will be navigable for ships of up to 10.000 GRT over the 660 km long stretch from Yichang to Chongqing (Figures 2 and 3).

After completion of the entire project, goods ships will pass through the five-chamber lock chain (already in operation), a process that takes ca. 3 hours (Figure 4). Passenger ships will be transported by the ship lift in a much shorter journey time of around one hour (the actual lifting time is a maximum of 21 minutes at a lifting speed of 0,2 m/s).

The ship lift in the Three Gorges Project has special constructional characteristics that are significantly different from those of all known ship lifts built up to now [1] (Table 1):

- the maximum lifting height of 113 m is around three times that of German ship lifts,
- the chamber dimensions and therefore the weights to be moved using the counterweight principle (ca. 34000 t) are greater than in any ship lifts built up to now,
- as part of an enormous dam complex with power stations, flood protection and two chains of locks, the ship lift is subject to short-term operational water level fluctuations of up to 50 cm per hour on the downstream side,
- hydrological water level fluctuations of 30 m on the upstream side and 11,8 m on the downstream side require special construction measures at the upper and lower bays,
- since the ship lift is primarily for use by passenger ships, particularly high safety standards are required.

2 Initiation of the project

Germany has long-term experience of the construction and operation of vertical ship lifts [4]. The first vertical ship lift to be mentioned in documents was located at the Freiburger Mulde near Halsbrücke in Saxony and allowed ore carrier with dimensions of 18 m x 2 m to be raised and lowered over a height of 8 m using the 'dry method'. Today, four vertical ship lifts with lifting heights between 13 m and 38 m are in operation in Germany. An additional new ship lift at Niederfinow on the Havel-Oder Waterway near Eberswalde, with a lifting height of 36 m is being planned by the water and navigation authorities and is currently in the tender planning phase. It will supplement an existing ship lift constructed in 1936 which, even today, is still remarkable for its robustness. The dimensions of the chamber of the new Niederfinow ship lift have been designed for modern ships. Its supporting structure is made of reinforced concrete, while the main supporting structure of the existing ship lift is made of steel. The owner and planner is the Wasserstraßen-Neubauamt (office for the construction of new waterways), Berlin.

The Bundesanstalt für Wasserbau, Karlsruhe (German Federal Waterways Engineering and Research Institute, referred to in this article as the BAW) supported the planning process with ad-

vice, especially on the choice of the safety and drive systems for the lift chamber. These plans became known to the owner and operator of the Three Gorges Dam, the China Three Gorges Project Corporation (CTGPC). In late 1999, CTGPC commissioned the BAW to carry out a feasibility study [2] on the drive and safety systems for the planned ship lift in China [3]. The feasibility study also covered the chamber, hydraulic steel construction aspects and hydraulic systems, as well as earthquake considerations. The feasibility study, under BAW leadership, involved a number of engineering firms which had taken part in the preliminary planning for the new Niederfinow ship lift (Krebs und Kiefer, Germanische Lloyd, Spezialbau Engineering GmbH).

Based on assessments of the drives used in existing ship lifts in Germany and in other countries, e.g. rope winch drive (Strépy Thieu), toothed rack and pinion (Lüneburg), nut with driven spindle (Henrichenburg), spindle with driven nut (Rothensee) and pinion rack and pinion (old lift at Niederfinow), pinion drive was selected as the preferred alternative for the new Three Gorges ship lift. The assessment of the different safety systems, which are closely linked with the drives, e.g. drum brake (Strépy Thieu), nut post (old lift at Niederfinow, Lüneburg) and lock nut on spindle (Henrichenburg, Rothensee), favored the nut post as the most reliable safety system [3]. Both principles show parallels with the newly planned ship lift at Niederfinow.

Pinion drives are characterized by their great robustness. The ship chamber safety mechanism is of particular importance. At any height, it prevents uncontrollable working conditions that could arise as a result of accidents by safely locking the chamber onto the concrete structure. Accidental loads can occur, for instance, if the chamber is unexpectedly emptied (partially or completely). Water losses of this type are usually caused by major leaks in the chamber seals or by damage to the chamber. Another typical design consideration is chamber uplift in the lower position in the case of a chamber basement that has filled with water, e.g. as a result of unusually high water levels. In the ship lifts at Lüneburg and Niederfinow, the chamber safety mechanisms have always worked perfectly in these unusual load cases.

Following intensive scrutiny of the study, CTGPC made a decision in favor of the solutions suggested in the feasibility study. Additional engineering firms had, by then, been integrated into the next planning phases for the Niederfinow ship lift, and at CTGPC's request, the entire German engineering expertise on ship lifts was to be concentrated in the tender planning phase for the Chinese lift (Figure 5).

For this purpose, the two engineering firms Krebs und Kiefer International and Lahmeyer International had joined forces to form a project-specific joint venture named "German Design Group". Specialist planners were engaged as subcontractors for the areas of mechanical and electrical engineering and for control equipment technology. Germanischer Lloyd was integrated into the joint venture as a consultant on safety and operations.

The BAW construction department supported the owner as a panel of expert.

3 Project processing by the joint venture

Contract negotiations between the joint venture and the Chinese owner CTGPC were successfully completed in April 2004 (Figure 5). The subject of the engineering contract, which is based on the FIDIC standard contract, is the production of planning documents in English suitable for use in the tender process. This planning work should be completed in Spring 2006.

The planning work is divided into four phases:

- Phase A Familiarization with the project
- Phase B General Layout
- Phase C Preliminary Design
- Phase D Final/ Tender Design

The basic design principles were summarized in cooperation with CTGPC in a document entitled "Guideline for Design" [5]. This covers project-specific regulations, actions and materials.

The drawings and specifications produced in Phase D will enable the successful bidders to produce the shop drawings and then to carry out the actual construction. As a rule, the design and construction should conform to current German standards.

At the end of every planning phase, the Chinese side reviews the planning results and approves them as the basis for the next stage of planning.

4 Concrete structure

The supporting structure of the ship lift is made of reinforced concrete. Its overall dimensions are 119 m long, 169 m high and 57,8 m wide (Figures 6 and 7).

Passenger ships are transported vertically in the center between the reinforced concrete construction. The huge longitudinal shear walls have openings to allow maximum natural lighting and ventilation, which would be especially relevant in the case of a fire.

On each of the long sides of the chamber there is a pair of towers. There is a clear distance of 20 m between the towers in each pair. The towers are spanned at the top by a 21 m high sheave hall made of steel (Figure 8) and are additionally connected with each other by beams distributed over their height. In a longitudinal direction, the tops of the towers are coupled by the visitor platform and by the central control stand (Figure 9).

The chamber is connected with the counterweights by ropes that are guided over rope pulleys. Eight counterweight groups are located on each side of the chamber, each group being guided through a reinforced concrete shaft or along the side of a tower (Figure 10). The reinforced concrete shafts measure ca. 10 m by 16 m, and the reinforced concrete towers 40 m long and 16 m wide. The cross-section of each tower is composed of two lateral shafts and a slightly recessed area containing the elevator and staircase. The toothed racks of the drive and the nut post of the chamber safety mechanism are also installed in this area (Figure 14).

At the transition to the upper and lower bay respectively, there are individual transverse shear walls which are stiffened by beams and by the ceiling slab of the sheave hall. A further shear wall is located between each pair of towers (Figure 10). These shear walls are required to support the rope pulley beams and also to guide the counterweights.

The loads from the chamber and the counterweights – totaling ca. 320 MN – are transferred into the concrete construction via the rope pulley beams at the top of the structure (Figure 8). Each rope pulley beam spans from one transverse wall to the next and bears the load from one group of counterweights and the corresponding share of the weight of the chamber. 8 double rope sheaves with a diameter of 5 m are mounted in each field of the rope pulley beam. The rope sheaves are protected from external environmental influences by the sheave halls. A crane with a lifting capacity of 65 t is installed in each hall so that maintenance work can be carried out.

The supporting walls of the reinforced concrete structure are mostly 1 m thick. In areas where concentrated loads are transferred, the walls are thicker.

The concrete construction is designed for a useful life of 100 years. The standard areas are constructed using concrete of Chinese quality C 30, which corresponds to C 25/30. In areas of high

loads, Chinese C 35 is used, which practically corresponds to C 30/37. Standard areas are reinforced with steel of Chinese quality HRB 335 ($f_{yk}=335 \text{ N/mm}^2$). In areas of high loads, HRB 400 ($f_{yk}=400 \text{ N/mm}^2$) is used.

The foundations of the reinforced concrete towers are constructed in a 36 m deep excavation pit where there is rock (granite) with a stiffness of 30.000 MN/m^2 . The calculated settlement under the entire load from the construction amounts to only a few millimeters. The calculations for the foundations were made using a half-space model.

5 Steel construction

The 132 m long and 23 m wide steel chamber is built as a self-supporting structure. It hangs evenly from 128 ropes on each side, 16 ropes for each counterweight group (Figure 11). This results in a very even transfer of loads into the chamber. The ends of the chamber and around the machine rooms are the only areas where no ropes can be located, for structural reasons. The chamber is designed for a water depth of 3,5 m and has a freeboard of 80 cm. The clear distance between the fenders is 18 m. The useful distance between the anti-collision devices in front of the gates is 120 m.

As well as passenger ships with dimensions of 84,5 m length, 17,2 m width and a draught of 2,65 m, the chamber is also designed for pushed chains of barges of length 109,4 m, width 14 m and draught 2,78 m. The passenger ship has a water displacement of 3.000 t.

As well as DIN 19704 Hydraulic steel construction, DIN 18800 and the "Guideline for Design" [5] were decisive for the design of the chamber.

The chamber construction is an orthotropic plate. For longitudinal stiffening under the floor of the chamber, open profiles are used so as not to increase the uplift that would result from the catastrophic load case of a water-filled chamber basement. The main beams are 10 m high and 2,3 m wide three-cell box girders. The choice of these very stiff main beams guarantees that the entire construction is stiff enough to ensure that the chamber can function properly in all operational situations. The box girders have lateral openings to ensure adequate ventilation and to reduce the uplift volume. The steel construction is made of steel of Chinese quality Q 345, which is very similar to German steel quality S 355. The mechanical values for Chinese steel are also reduced according to the sheet thickness, compared with the nominal value.

The ropes connect the chamber and counterweights. Each counterweight group consists of 16 individual weights. Each rope connected with the chamber is guided over the rope sheaves and connected with one individual weight. This method of handling the loads ensures that all ropes bear the same load. The 16 individual weights per shaft are combined to form a group using a safety frame which ensures that each individual weight is prevented from falling if its rope breaks. The ropes have a nominal strength of 1960 N/mm² and a diameter of 74 mm.

The machine rooms are located at the quarter points of the chamber on both long sides and extend into the concrete towers (Figure 11). The machine rooms house both the chamber drive and the chamber safety mechanism (Figure 12). The electrical equipment and controls are located in watertight rooms in the level below the drives.

The chamber is closed by a radial lock gate (Figure 13). Each gate segment has a radius of 3,1 m and is supported laterally in the main beams. When the gate is open, it disappears into the gate niche at the end of the chamber and is flush with the floor of the chamber. For inspection purposes, the gate can be moved into an overhead position.

The steel construction is designed for a useful life of 70 years, and the mechanical components for a useful life of 35 years. For the purposes of fatigue resistance inspections, 335 operating days per year and 22 hours per day are assumed. On average, 18 full journeys (each consisting of an ascent and a descent) per day are planned.

6 Guiding mechanisms

As well as normal operating loads, the ship lift is also subject to catastrophic loads, e.g. through earthquakes. This means that active longitudinal and transverse guidance of the chamber is necessary over the entire lifting height of ca. 113 m to allow controlled movement of the chamber under normal loads (operations) and deliberate load transmission in catastrophic cases. It is not possible for the chamber to swing freely (Figure 14).

The forces resulting from operations (e.g. as a result of wind) are relatively minor. Should an earthquake occur of the dimensions for which the ship lift was designed, the construction must be in a position to absorb the enormous forces (s. Chapter 10).

For cost reasons, there is no separate guiding equipment for normal operations and for the catastrophic case of an earthquake. The transverse guiding function is integrated into the

toothed rack of the chamber drive, while the longitudinal guiding function is combined with the earthquake support.

The transverse guiding equipment is located on the level of the electrical equipment rooms beneath the machine rooms (Figure 16). The guide carriage grips the two guide rails along the sides of the toothed rack and can transfer both compressive and tensile forces. A double-acting hydraulic cylinder with a continuous piston rod is installed on each transverse guide. On both guide axes, the hydraulic cylinders on one side of the chamber are linked by crossed diagonal connections with the hydraulic cylinders on the other side (Figure 15). This ensures that both cylinders always move in or out evenly and keeps the chamber in a central position between the reinforced steel towers. In this way, an expensive additional steering mechanism for the chamber could be avoided. The guide carriage moves close to the toothed rack. The guide rollers are pre-tensioned for the normal operational loads. In the case of an earthquake, the roller springs are fully compressed. The 2 m long runners of the guide carriage lock because of friction and are able to absorb the enormous forces (Figure 16).

The longitudinal guide system has several functions. At the holding points, it must be able to absorb not only the water pressure from the gate that is opened on one side (ca. 8 MN) and the jacking force from the clearance sealing mechanism (ca. 2 MN) but also forces from possible ship impacts. It also takes on forces resulting from earthquakes of up to 20 MN. Because of the necessarily high stiffness of the reinforced concrete towers and the steel chamber, it is very important that the chamber is supported in a constraint-free way. This has been achieved using a mechanically very simple point support, via a bending beam installed transversely to the chamber. This absorbs its loads via a point support in the longitudinal axis of the chamber and transfers the loads laterally into the reinforced concrete towers by means of its stiffness. The steel girder, a box girder with a cross-section of 2 m x 4 m, penetrates the main beam beneath the floor of the chamber. Between the main beam and the reinforced steel construction, the bending beam grips a reinforced concrete projection by means of hammer-like construction, and transfers its loads from here evenly to the right and to the left into the reinforced concrete construction (Figure 17). The middle support for the longitudinal guiding system is designed for a load of almost 30 MN and is an elastomer bearing. Loads from the chamber are transferred via the chamber floor and via the transverse beams which are joined next to the bearing by additional steel sheets to form a box girder. The bearing is installed on a girder-grid-like substructure in order to be able to transfer the concentrated loads into the steel construction. For this purpose, additional diaphragms between the transverse beams are required to ensure spreading of the loads.

During operations, there is a gap of 5 mm between the longitudinal guide system and the guide rails, which is ensured by pre-tensioned guide rollers.

Through the statically determinate chamber guide system, both the reinforced concrete towers and the chamber can deform without constraints. The transverse and longitudinal guide systems can, each independently of the other, transfer the loads which arise.

7 Drive

The mass of the chamber and the normal amount of water in it are balanced by the counterweights. The drive system is designed for a water level difference of 10 cm.

The chamber is driven by four pinions that extend into toothed racks built into the towers. Each pinion is elastically mounted on a bearing bracket in the machine room in such a way that movements can be compensated (Figure 18). Because of the chosen kinematics of the mounting, only minor relative deformations between the pinion and the toothed rack result. Guide carriages behind the toothed rack ensure that the pinion is always gripped by the rack. The pinion is driven on both sides by shafts, each of which is directly connected with an electric motor via driving gear.

To deal with the rare case that one or even both motors at a drive station are out of action, all drives are connected with each other by synchronizing shafts under the chamber. In this situation, the missing drive moment is transferred to the affected area by these shafts, so that the chamber journey can be completed as planned.

The chamber is motor-driven on both the ascent and descent. On the ascent, the chamber is moved with a slightly larger water level difference. On the descent, the chamber is slightly less full, so that the counterweights tend to pull it up, and as a result it must be pulled down using motors. The construction is, however, designed in such a way that the lift can be operated in generating mode. Motor-driven mode leads to alternating stresses on the pinions which were taken into consideration in the design process.

8 Chamber safety mechanism

By securely locking the chamber onto the concrete construction, the chamber safety mechanism prevents uncontrollable operating situations which could otherwise result from accidents. The chamber safety mechanism is a combination of a nut post and a rotary Archimedean screw. The nut post is a cast steel column construction, slit longitudinally and with an internal thread, that is

built into the concrete construction over the entire lifting height. Inside the nut post a spindle moves, revolving around its own axis. This spindle, for which the term rotary Archimedean screw is also used, is driven directly by the chamber drive system. Because of a direct mechanical coupling via a shaft system between the drives and the rotary Archimedean screws of the chamber safety mechanism, the rotary Archimedean screws always move synchronously with the drives in a force-free way. During normal operations, there is a certain amount of play between the rotary Archimedean screw and the nut post, so that they do not touch each other. The rotary Archimedean screw is supported by articulated rods mounted on the upper and lower corner pieces of the chamber (Figure 19). The upper corner piece is connected with the chamber by a pin construction and can be dismantled for repair work on the rotary Archimedean screw.

If the pinion is overloaded, e.g. by a higher water level difference or by a loss of water, it deflects and escapes its load. In such a case, the chamber locks into the nut post via the rotary Archimedean screw and is immediately stopped.

The nut post is installed over the entire height in sections ca. 5 m long. Because of the very high degree of accuracy required, it is not possible to build it into the first stage concrete. Cavities are therefore created in the first stage concrete in which steel girders can be embedded in a next step – after completion of the towers. The flanges of the steel girders have block connectors on the side towards the nut post and are flush with the second stage concrete. This measure considerably increases the level of accuracy. However, for the installation of the nut post, this step is not sufficient. In a final step, the nut post, which also has block connectors on its rear side, is adjusted. The block connectors now engage directly. The joint between the block connectors is designed to compensate for a maximum of 2 cm. Following final exact adjustment, the joint is poured using high-strength low-shrinkage mortar. Vertical load transfer now takes place via the block connectors. The tensile forces resulting from the eccentric load transfer are returned to the concrete construction by means of screws and tendons.

9 Ship chamber locking mechanism

At its upper and lower holding points, the chamber is locked both vertically and horizontally. This ensures that additional vertical loads, e.g. through a change in the water level, do not lead to additional loads on the driving pinion. Horizontal loads, e.g. from the impact of a ship, can easily be absorbed in the same way.

Vertical locking takes place at the outermost point of each concrete shaft (Figures 14 and 20). Through a vertical cylinder, two horizontal pincers are positioned in two lateral locking pockets located in the concrete. The pincers are then extended horizontally and pre-tensioned vertically

(Figure 20). For safety reasons, the piston of the vertical cylinder is then blocked so that it cannot yield even if the oil pressure falls.

In a longitudinal direction, the chamber is also locked in the longitudinal guide via the jacking rail. In the jacking rail, the longitudinal guide is friction-locked with the concrete via an eccentric tappet. Horizontal loads arising from the gate that is open on only one side and from possible ship impacts can easily be absorbed in this way.

Both the ship chamber locking mechanism and the jacking rail must be capable of functioning over the entire 30 m range of water fluctuation on the upstream side (145 m to 175 m). On the downstream side, water level changes of up to 11,8 m (62 m to 73,8 m) can occur.

10 Load cases, in particular earthquakes

The concrete components have been reviewed with respect to the decisive civil engineering design situations in ZTV-ING and/or the DIN specialist reports 100-102, and the hydraulic steel components according to DIN 19704 on the basis of the new norm concept. Additional load cases were added in the basic design principles ("Guideline for design") [5] by agreement with the owner and the owner's advisers, the Bundesanstalt für Wasserbau.

Special load cases must be investigated in addition to the normal load cases like water filling, wind loads, traction loads and guiding forces. These cases include impacts from docking ships, sunken ships, an empty chamber and a ship chamber subject to uplift. The load case 'earthquake' is of very great importance for the construction. In addition to the loads resulting from moving masses, information about the height of the waves in the chamber is significant in order to be able to judge whether water can slosh out of the chamber [6].

The actions for the earthquake load case were defined according to the Chinese earthquake norms for hydraulic structures. The ship lift is located in Zone VI of the Mercalli scale (Figure 21). Because of the very high safety requirements, the construction was designed for Zone VII with a basic acceleration of 0,1 g (1 m/s^2) with a probability of occurrence of once in 5000 years. Since no digitally recorded earthquake data is available for this area, the design was based on artificial earthquake information generated by the internationally recognized SIMQKE program developed by the Massachusetts Institute of Technology. The components were designed according to Eurocode 8 (Figure 22).

The objectives are to ensure that in the case of an earthquake, the safety of human life (above all) is guaranteed and disproportionately large financial damage is avoided. As a result, only small relative displacements ($\approx \pm 8\text{-}10 \text{ cm}$) are permissible between the chamber and the guide

system attached to the concrete construction. The functioning of the chamber safety mechanism must be guaranteed in every operational position.

In the case of an earthquake, the forces are optimally absorbed via a statically determinate support (Figure 23). The mechanisms of this support are installed on the guide equipment of the chamber in such a way that they only take effect in an earthquake. As a result, no additional embedded parts in the concrete construction are necessary, and the earthquake supports are not subject to wear during normal operations.

The forces in a longitudinal direction amount to a total of 30 MN (earthquake and other horizontal forces), and in a transverse direction to 4,5 MN at each supporting point; these are safely transferred into the concrete construction via the earthquake guides.

11 Deformations

As well as the purely static calculations for the individual components, the deformations (Table 2) play a decisive role in the reliable working of the ship lift. The mechanical components, especially the drives, chamber safety mechanism and chamber gates can only tolerate minor deformations, in contrast with the usually large deformations of the entire system under the enormous loads involved here, and with the normally relatively large dimensional inaccuracies of concrete construction. This situation places high demands on the execution of the concrete construction, the mechanical components and of the embedded parts in particular.

12 What happens next?

After completion of the tender planning phase in Spring 2006, the tender process for the ship lift is planned, so that the contract can be awarded in the same year.

The Chinese owners expect to put the new ship lift – the world's largest at that date – into operation in 2009 / 2010.

13 Parties involved in the planning work:

Joint Venture

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