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REVIEW OF STRUCTURAL DEVELOPMENT OF DAMS WITH AN EMPHASIS ON THE CONSTRUCTION OF THREE GORGES DAM

Abstract

Dams are hydrotehnic engineering structures that have undergone significant advancement throughout history from an engineering standpoint, and today they represent some of the most complex constructions. Additionally, they play a crucial role in the economic development of many countries. Four basic types of dams have been developed: embankment, gravity, buttress, and arch dams. Each of them poses unique challenges that require significant efforts from engineers, which include the constant development and application of new technologies. One of them is the Three Gorges Dam, which represents the largest gravity dam, as well as the largest hydroelectric complex in the world. The technology of the project is extremely complex, and together with the comprehensive benefits to the community, makes the project more challenging than any other hydro project in the world.

Keywords: embankment dam, gravity dam, buttress dam, arch dam, Three Gorges Dam, hydrotehnic engineering

ПРЕГЛЕД КОНСТРУКТИВНОГ РАЗВОЈА БРАНА СА АКЦЕНТОМ НА ИЗГРАДЊУ БРАНЕ ТРИ КЛАНЦА

Сажетак

Бране су хидротехничке конструкције које су кроз историју доживјеле значајан напредак у инжињерском погледу, и данас представљају једне од најкомплекснијих конструкција. Поред тога, имају кључну улогу у привредном развоју многих земаља. Развијена су четири основна типа брана: насуте, гравитационе, контрафорне и лучне. Иза сваког од њих се крију јединствени проблеми који захтјевају значајна залагања инжењера, који захтјевају стални развој и примјену нових технологија. Пројекат Три Кланца представља највећу гравитациону брану, а уједно и највећи хидроенергетски комплекс на свијету. Технологија пројекта је изузетно сложена, и заједно са свеобухватним користима за заједницу, чини га изазовнијим од било ког другог хидропројекта на свијету.

Кључне ријечи: насуте бране, гравитационе бране, контрафорне бране, лучне бране, брана Три кланца, хидротехничке конструкције

1. INTRODUCTION

1.1. HISTORY

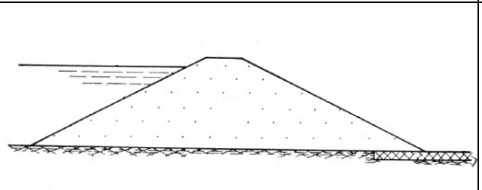
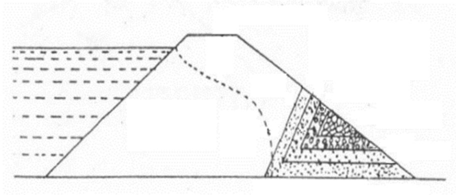
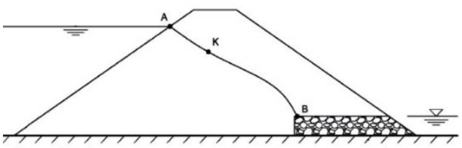
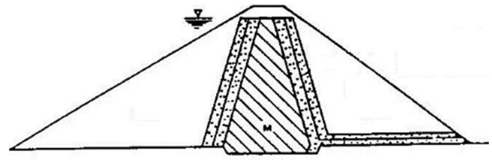
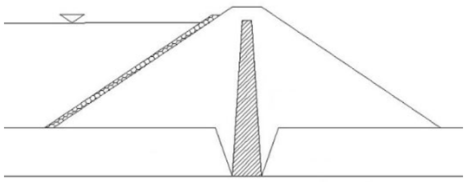
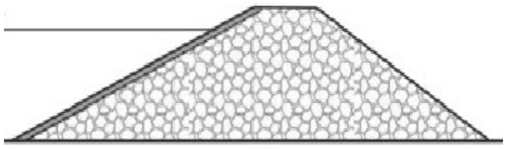
People have been constructing hydotehnic structures since ancient times, such as low earth dams, irrigation canals, spring intakes, etc. Today, remnants of these structures cannot be found as they were constantly exposed to water and atmospheric environment, but it is assumed that they existed.
It is believed that the first hydotehnic structures were irrigation canals, constructed by the Sumerians around 5.000 years BCE. Additionally, in Egypt, unlined irrigation canals have been built around 5.000 BCE. According to Herodotus, the earliest engineering works were associated with the construction of the city of Memphis on the Nile River, where embankments were dug, the old riverbed was drained, and the river channel was diverted between hills. At that time, the Kosheh Dam was built, which was 15 meters high and 450 meters long at its crest, [1].
Today, remnants of the foundation of the Sadd el-Kafara Dam exist in the now-dry Garawi Canal, approximately 32 kilometers south of Cairo. This dam was built around 2.900 BCE. It stood about 11 meters high and had a crest length of around 107 meters. The dam walls were made of hewn stone, and the reservoir capacity was approximately 570.000 cubic meters. During the first flood, the reservoir was too small to accommodate the floodwater, resulting in the flooding of the dam and the collapse of its central part. After that, dams were not built in Egypt for several hundred years.
Throughout the valleys of the Euphrates and Tigris, there existed numerous irrigation canals even before 2.100 BCE. During the construction of canals to divert water from the Tigris, a massive stone embankment dam was built. To divert the nearby tributary of the Tigris, the Atem River, the Atem Dam was constructed, the remnants of which could be seen at the beginning of this century. It was a stone masonry dam, diverting water from the river into two channels. Another significant dam on the Tigris is the Marduk Dam, which was built around 2.000 BCE. It was made of earth materials and had a height of about 12 meters.
In the area of present-day Yemen, around 950 BCE, the Andra, Adshma, and Marib dams were constructed. The largest among them was the Marib Dam, estimated to be 37 meters high and 3.200 meters long. The Andra and Adshma dams were built in canyons and are believed to have been 15 to 20 meters high.
On the island of Ceylon, present-day Sri Lanka, many dams and irrigation systems were built. Remains still exist today near the old capitals. The Kalaba Reservoir, which served for irrigation near the capital Anuradhapura, was an embankment dam with a height of 24 meters and a length of 6.000 meters. In 430 BCE, the Basavakulam Dam was built, followed by the Tisa Dam in 407 BCE, which were lower but longer.
Near the old capital of Petra, now in Jordan, several centuries before BCE, a stone embankment dam was constructed, with a height of 14 meters, as well as the gravity dam of Kurnubu in Israel. These two dams have been preserved to this day, [1].

1.2. TYPES OF DAMS

1.2.1. EMBANKMENT DAMS

The oldest and most widespread type of dams are embankment dams. Since prehistoric times, there has been a need for dam construction due to human dependence on water. Especially in countries such as Egypt, the Middle East, and India, where dry periods occur, dam construction has been essential to preserve seasonal rainfall. In Europe, the construction of these dams began later, after the Industrial Revolution when there was a greater need for water due to urban and industrial development [2]. Embankment dams are constructed by controlled deposition and compaction of locally available materials. These dams resist forces through their own weight, transferring the load to the ground over a much larger surface area compared to concrete dams, thereby reducing stresses in the soil. The main issue with this type of dam is its susceptibility to erosion due to water action. Depending on the material they are constructed from, dams are divided into earth-filled and rock-fill dams. Throughout history, these dams have been extensively built but also frequently collapsed. Possible reasons include dam overtopping, which is accompanied by erosion. Then there's internal erosion, which involves the removal of particles of incoherent material, leading to the formation of a large opening through the foundation of the structure. In case of high pore pressure in the embankment or foundation, downstream slope sliding and dam failure occur. On the other hand, an additional advantage of these dams is much lower costs of constructing compared to the costs of constructing concrete dams, [3]. Some types of embankment dams are shown in Table 1.

Table 1. Types of embankment dams, [4], [5], [6], [7], [8], [9].

Homogeneous type of earthen dam	Modified homogeneous type of earthen dam with a filter and a downstream leg made of selected stone
	
A modified homogeneous type of earthen dam with a drainage carpet under one downstream part of the dam	Zoned type of earthen dam
	
Diaphragm earthen dam type	A rock dam
	

An example of an embankment dam is the Vlasina Dam, which is 34 meters high, has a volume of 365.000 cubic meters, and its reservoir has a volume of 165.000.000 cubic meters. This dam is used for hydroelectric power generation and irrigation [1].

The Nurak Dam, located on the Vakhsh River in Tajikistan, Fig. 1, has a unique construction because its core is built with concrete, and then the dam is embanked with compacted earth. The Nurak Dam is 304 meters high and has a length of 700 meters, [3].

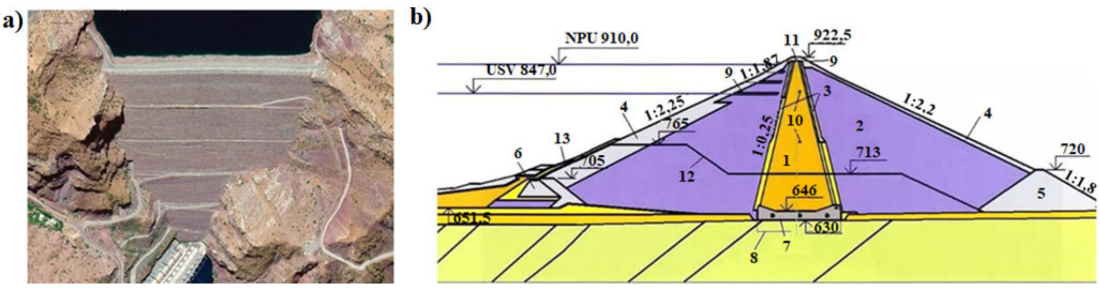


Figure 1. a) The Nurek Dam, [10]; b) The cross-section of the Nurek Dam: 1 – sandy loam core; 2 – shells of coarse; 3 – filters (d=0-5 mm and d=0-50 mm); 4 – oversize rockfill surcharge stones on upstream slope (20-40 m thickness), downstream slope (5-10 m thickness) and downstream cofferdam; 5 – downstream cofferdam of oversize rockfill; 6 – upstream cofferdam; 7 – concrete block; 8 – consolidation grout and grout curtain; 9 – anti-seismic belts; 10 – control gallery 2x2 m; 11 – control gallery 4x4 m on dam crest; 12 – contour of first-stage dam construction; 13 – temporary clay blanket of first-stage dam construction, [11].

1.2.2. BUTTRESS DAMS

We distinguish dams with buttresses, which have either an upstream massive head or a flat upstream slab. There is significant freedom in shaping these dams during the design process [2]. Buttress dams resist sliding and overturning by their own weight as well as the vertical components of hydrostatic force, i.e., the weight of water above the sloping upstream face, Fig. 2. Unlike massive gravity dams, buttress dams only have buttresses-wall supports on the downstream side and reinforced concrete slabs on the upstream face. Sometimes even the buttresses can be hollow, making this dam concept lightweight. In these dams, the structure can be founded on the dam's foundations, reducing the load-bearing area, but increasing the stresses in the foundation joint. Although less concrete is required for buttress dams compared to gravity dams, the construction costs are higher due to the need for more complex formwork, resulting in increased expenses and requiring a more skilled workforce. There are multiple-arch dams where instead of reinforced concrete slabs between the buttresses, arches are installed. This solution significantly reduces the amount of reinforcement required but increases the complexity of construction. Massive buttress dams, whose upstream face is formed by thickening the buttresses themselves, are devoid of tensile stresses, so the heads are made of unreinforced concrete, but this increases the weight of the dam. The weight can be reduced by hollowing out the buttresses, further complicating the concrete pouring work, [3].

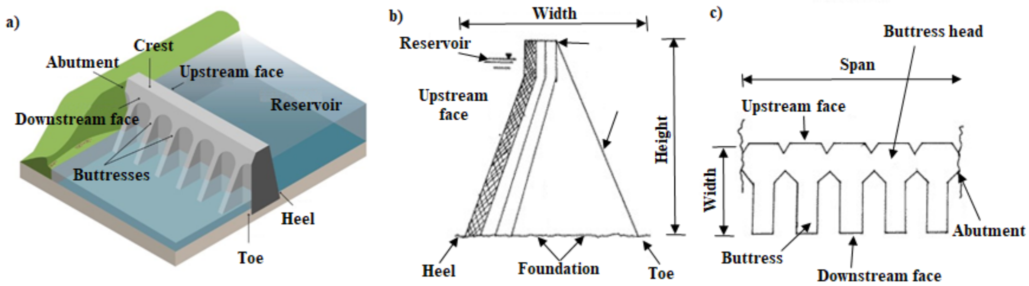


Figure 2. a) Buttress dam, [12]; b) Cross-section, [13]; c) Top view, [13].

An example of a buttress dam is the Bajina Bašta Dam, Fig. 3, which was built in 1996. It has a height of 90 meters and a crest length of 461 meters. The reservoir volume, used for hydroelectric power generation, is 340.000.000 cubic meters [1].

Figure 3. a) The Bajina Basta Dam, [14]; b) Construction of the Bajina Basta Dam, [15]; c) Cross-section of the Bajina Basta Dam, [16].

1.2.3. ARCH DAMS

Arch dams represent structures defined by their arch-shaped or curved form, with the load primarily transmitted to the abutments. The safety and stability of the structure depend on the physical-mechanical characteristics of the material from which the considered structure is built and the bearing capacity of the foundation soil in general, which involves the foundation bond and abutments of the arch dam. Arch dams represent a more economical construction method, being 40 to 60% more cost-effective than gravity dams, but they require better foundation conditions and more complex construction technology. Additionally, the design process of arch dams is significantly more demanding. The construction of arch dams necessitates constant and coordinated supervision throughout all construction phases, with particular emphasis on concrete quality, the method of concrete placement in segments, monitoring of the temperature of the poured concrete mass, and continuous observation and measurement of dam structure and abutment displacements.

An arch dam can be represented as a continuous vault (shell-like structure), supported on three sides (early builders considered it 'wedged'). It is a statically multiple-indeterminate structure, which, in order to be more easily analyzed, must be divided into elements of simple shapes [2].
With the increasing demand for electric power, the number of constructed dams is rising, leading to dams being built in increasingly unfavorable terrains, including unfavorable gorges in terms of span, height, and quality of rock mass. At the Gordon Arch Dam in Australia, Fig. 4, an elliptical shape was adopted as more suitable for transferring forces from the dam to the abutments.

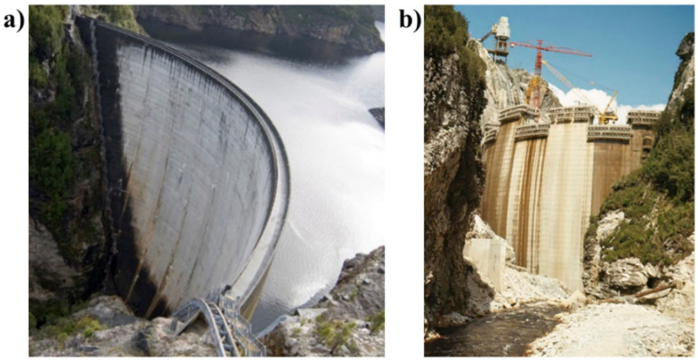


Figure 4. a) The Gordon Dam, [17]; b) Construction of the Gordon Dam, [18].

It should be emphasized that a special group of arch dams consists of arch-gravity dams whose base in the foundations has a ratio of (0.33 - 0.65) H, where H is the height of the dam. Due to the considerable thickness of these dams, the majority of the load is transferred to the valley floor, while a smaller portion of the load is transferred to the abutments. The Jablanica Arch Dam belongs to this type of dam, Fig. 5.

Figure 5. Jablanica Dam, [19].

In the case of reservoirs with large arch dams, the discharge of large volumes of water is carried out via lateral spillways on the crest of the dam or outside the dam body, with a high-velocity flow on the slope and a spillway in the riverbed, as well as through the bottom outlet. This procedure aims to mitigate the impact of the water surge, which is discharged via spillways, on the downstream water level of the hydroelectric power plant or to protect the riverbed from erosion. The geometric design criteria for arch dams are stricter than for other types of dams because the arch action is limited by the L/H ratio, where L is the length at the crest and H is the height of the dam. It was once believed that an arch dam could not be constructed if the L/H ratio exceeded 3.5.
Control galleries and 'passerelles' are used for injecting radial joints. In the case of the annular and longitudinal injection system, where the injection mixture is supplied from the downstream face, 'passerelles' are used, [2].

1.2.4. GRAVITY DAMS

A gravity dam is a solid concrete structure that resists external forces by its own weight, hence it has a large volume and a wide base. They are usually (straight), however, sometimes they can be curved or angled to better adapt to the topography of the terrain. These are the most common types of concrete dams and the simplest to design and construct.

The design of gravity dams involves collecting and considering geological, hydrological, and seismic data, conducting studies on the site and type of dam, and researching the materials and characteristics of the foundation. After conducting these investigations and studies, the design of the dam and its analysis follow. The project ensures the arrangement of project-defined structures, cross-section profiles, as well as the location and details of other features of the dam such as monolithic and structural joints (expansion joints), galleries, chamber gates, channels, and injection and drainage facilities.

Gravity dams consist of spillway and non-spillway sections, Fig. 6, [20]. If the dam is used for electricity generation, part of the non-spillway section of the dam usually serves as an intake section with an embedded pipeline leading to the power plant, [21].

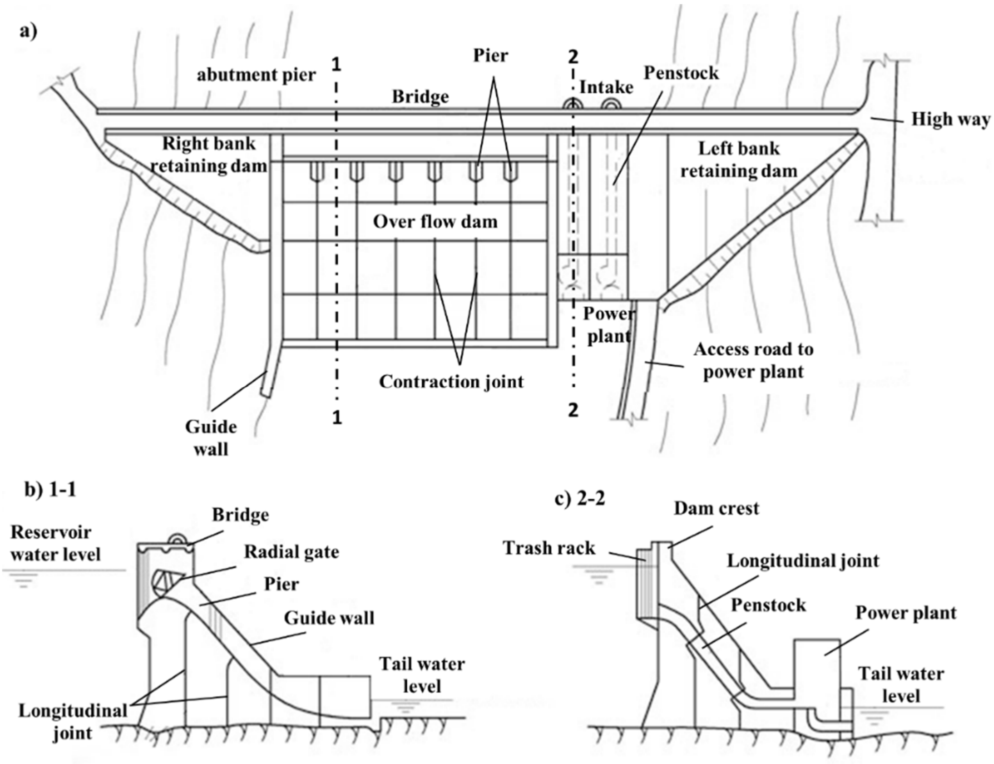


Figure 6. a) Top view of gravity dam; b) Cross section of over flow dam; c) Cross section of power plant.

The non-spillway sections have a uniform downstream slope of about 1 : 0.7-0.8. The upstream side is usually vertical, but sometimes batter slopes are added to increase resistance to sliding or to locate the resultant within the boundary area of the middle third.

Both faces are sometimes provided with a fillet at their intersections with the foundation to reduce stress concentrations. The crest of the dam is typically dimensioned to provide a roadway and should have sufficient strength to withstand ice pressure and the impact of floating objects. In areas of significant seismicity, the mass of the crest should be minimized, and the interruption of the slope at the junction of the crest and downstream slope should be gradual or eliminated.

The spillway section has a rounded crest, and at the lower part, a sharp-profiled weir. The downstream side slope is set to tangent the crest curve and also the curve at the junction with the stilling basin. Piers are installed for intermediate support when a bridge is provided over the spillway and, for controlled crests, also to support gates. Gated outlets, when required to regulate downstream flows for navigation, irrigation, or other purposes, are usually placed in the spillway monoliths.

The powerhouse typically contains trash racks, intake pipes, stop logs, discharge gates, and penstock pipes. When there is sufficient space, the power plant is located immediately downstream of the intake section. For low-head dams, the intake, power plant, and discharge pipes are often one structural element, [21].

Table 2. Top 4 largest gravity dams in the world by capacity, [22], [23], [24], [25], [26].

View of Dams	**Description**
	Three Gorges Dam Location : Yangtze River, China Height: 181 m Length: 2.335 m Capacity: 22.500 MW The Three Gorges Dam is the largest dam globally, both in terms of height and power generation capacity. It's a colossal structure on the Yangtze River, serving flood control, electricity generation, and navigation.
	Itaipu Dam Location: Paraná River, Brazil/Paraguay Height: 196 m Length: 7.919 m Capacity: 14.000 MW The Itaipu Dam is a binational project between Brazil and Paraguay. It ranks as one of the largest hydroelectric power plants in the world and provides a significant portion of both countries' electricity needs.
	Guri Dam Location: Caroni River, Venezuela Height: 162 m Length: 1.300 m Capacity: 10.235 MW Guri Dam is a crucial component of Venezuela's power generation infrastructure.
	Tucuruí Dam Location: Tocantins River, Brazil Height: 78 m Length: 12.750 m Capacity: 8.370 MW The Tucuruí Dam represents one of the key facilities for electricity production and the development of the state.

The Table 2 shows the four largest gravity dams in the world, with the Three Gorges Dam in first place, described in detail below.

2. THREE GORGES DAM

The Yangtze River is the largest in China and the third largest in the world, with a main stream length of 6300 kilometers. The total volume of water flowing into the sea averages 960 billion cubic meters annually. Its total water potential reaches about 268,000 MW, with usable reserves around 197,000 MW. The Three Gorges of the Yangtze is one of the places holding the largest water reserves in the world.

The Three Gorges Dam is a large-scale hydroelectric project with enormous comprehensive benefits in flood prevention and control, electricity generation, transportation, and water supply.

The dam project is crucial for controlling the Yangtze River. Its main tasks include preventing and mitigating catastrophic floods in the middle and lower reaches of the river, particularly in the Jingjiang section of the main stream, providing electricity to central and eastern China and the eastern province of Sichuan, and improving navigation conditions in the middle reaches of the river.

The dam controls a drainage area of about one million square kilometers, with an average annual flow of 451 billion cubic meters. The dam is a concrete gravity dam, with a crest length of 2335 meters and a maximum height of 175 meters. The main construction volume of the project involved excavating 10.28 million cubic meters of earth and rock, approximately 31.98 million cubic meters of embankment, around 27.94 million cubic meters of concrete, and 460,000 tons of reinforcement. Calculated at the end of May 1993 prices, the total cost was estimated at 50.09 billion yuan ¥.

The first phase, including preparatory work, lasted for 5 years, from 1993 to 1997, representing the formation of the dam. The second phase lasted for 6 years, marked by the operation of the first group of generating units in 2003. The third phase also lasted for 6 years, until 2009, encompassing the start of operation of the left hydroelectric plant and ship lock, as well as the construction of the section of the dam where the right hydroelectric plant will be located. The entire project was completed in 17 years as planned, [27].

2.1. THREE GORGES PROJECT

The Three Gorges Project, in addition to the dam, includes two separate hydroelectric power plants, as well as sections dedicated to water traffic. After extensive research, it was decided that the spillway section would be located in the middle of the riverbed, while the power plants would be situated on the sides. The spillway section is 483 meters wide and has 23 spillway gates at a height of 90 meters and 22 surface temporary outlets. The left hydroelectric plant is 643.7 meters long with 14 generator turbines, while the right one is 584.2 meters long with 12 generators. Additionally, on the Baiyanjian Mountain, located on the right bank, there is an underground power plant with 6 hydro turbines, Fig. 7. The transportation section consists of a ship lock for both directions, designed for ships with a cargo capacity of 10,000 tons, and the crossing takes about 4 hours. For smaller cargo and passenger ships, there is a ship lift, which speeds up transportation, with a maximum carrying capacity of 3000 tons. These facilities overcome the water level difference of 175 meters between the two sides of the dam, [28].

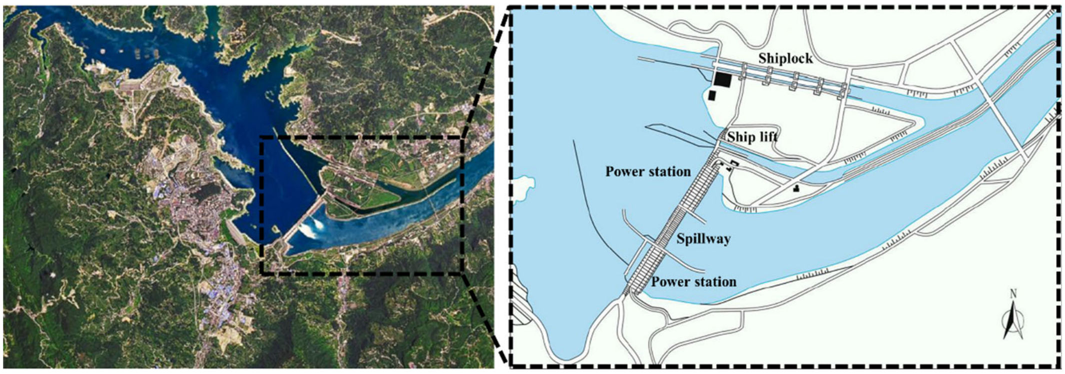


Figure 7. Layout of the Three Gorges Project, [29], [27].

2.1.1. RESETTLEMNT

The Chinese government has made a significant effort in relocating people, and the relocation officially began in 1993, when construction started eight years after pilot projects began in 1985. By the end of 2004, 45 billion yuan had been invested in relocating 980,900 people, accounting for 87% of the total number, including 658,300 people from urban areas and 322,200 from rural areas, with 13 new cities and county seats (fully or partially submerged by the reservoir) rebuilt according to the principle of rehabilitating original standards, size, and functions, significantly improved in terms of land space, transportation, telecommunications, electricity supply, and water supply. A total of 39 million square meters of houses and buildings have been completed, of which 31 million square meters, or 89%, have been rehabilitated. Out of the total number of factories and mines, 1428, or 88%, have been relocated; 1105 kilometers of roads have been constructed, which is 135% of the total planned length; and 2955 kilometers of power lines have been installed, accounting for 90% of the total planned length [27].

2.1.2. CONSTRUCTION

The project officially started in 1993 with the efforts of nearly 20,000 employees from the design, engineering, and supervision sectors.

The river was successfully dammed in November 1997, with the completion of the auxiliary dam before the start of the flood season, which endured tests from eight major flood waves in 1998, ensuring the safety of the construction site. In 1999, the construction of the dam transitioned from the excavation phase to mass concrete pouring, setting a world record for annual concrete pouring with 4.58 million cubic meters, averaging 554,000 cubic meters per month. However, the record was surpassed the following year, with 5.43 million cubic meters of concrete poured, Fig. 8.

In June 2003, the reservoir of the dam reached a height of 135 meters, and in 2004, the dam successfully halted approximately 500 million cubic meters of floodwaters, demonstrating its initial function of flood defense. By November of the same year, the water level of the artificial lake had reached a height of 139 meters, providing initial confirmation of the necessity of constructing such a massive structure. By the end of 2004, the financial resources invested in construction had reached 66.043 billion yuan, with preparatory work and excavation of earth and rock amounting to 139 million cubic meters. Earthen embankments totaling 52 million cubic meters were constructed, and the total amount of concrete installed amounted to 26 million cubic meters. Additionally, it is important to note that machinery and electrical equipment weighing 97,100 tons were installed, and 177,100 tons of steel were used for various steel structures on the project site, [27].

a) b)

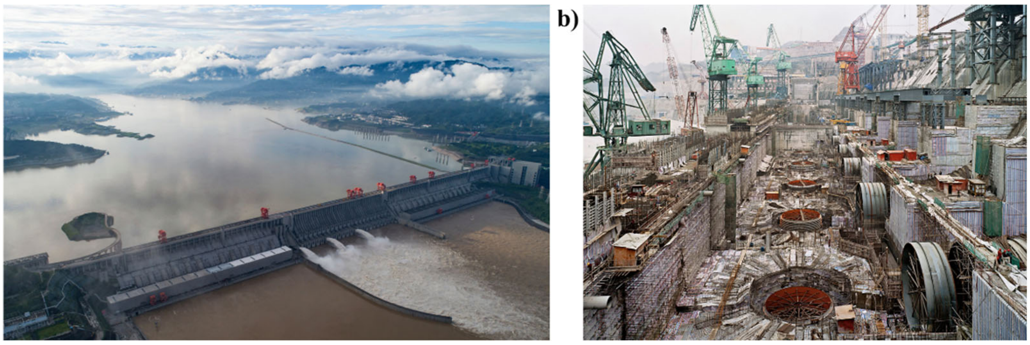


Figure 8. a) Three Gorges Dam, [30]; b) Construction of Three Gorges Dam, [31].

The entire process was accompanied by a rigorous quality control system, from the procurement of raw materials, equipment production, construction, through testing, experiments, and supervision. Regulatory bodies conducted independent oversight alongside a full set of on-site tests. World-renowned foreign companies were invited to provide consulting services and oversee the construction of key parts of the dam and equipment production. To enhance quality control, an expert group for quality inspection was established, composed of numerous academics from the Chinese Academy of Sciences and the Chinese Academy of Engineering, to conduct regular quality inspections and evaluations, [27].

2.1.3. KEY TECHNOLOGY OF THE GRAVITY DAM PROJECT

Due to the large capacity of floodwaters and the large number of discharge units, it is necessary for this part of the dam to be as short as possible. After several years of research, through optimization and adaptation of the shape and structure of the flow path, as well as the arrangement of gates and associated facilities, a successful implementation of staggered triple-layered large discharge openings has been achieved. The length of the leading edge of the flood release section of the dam is determined to be 483 meters, divided into 23 monoliths. One of the 23 foundation outlets, with dimensions of 7m × 9m, is located in the middle of each monolith, and the lower elevation of the inlet is 90 meters above sea level, Fig. 9. One of the 22 upper openings is placed over each transverse joint, with a spillway crest elevation of 158 meters and a width of 8 meters. Immediately below the upper openings and over the transverse joints, 22 lower diversion openings are installed, with dimensions of 6m × 8.5m. The lower elevation of the inlet is 56 meters or 57 meters above sea level, [32].

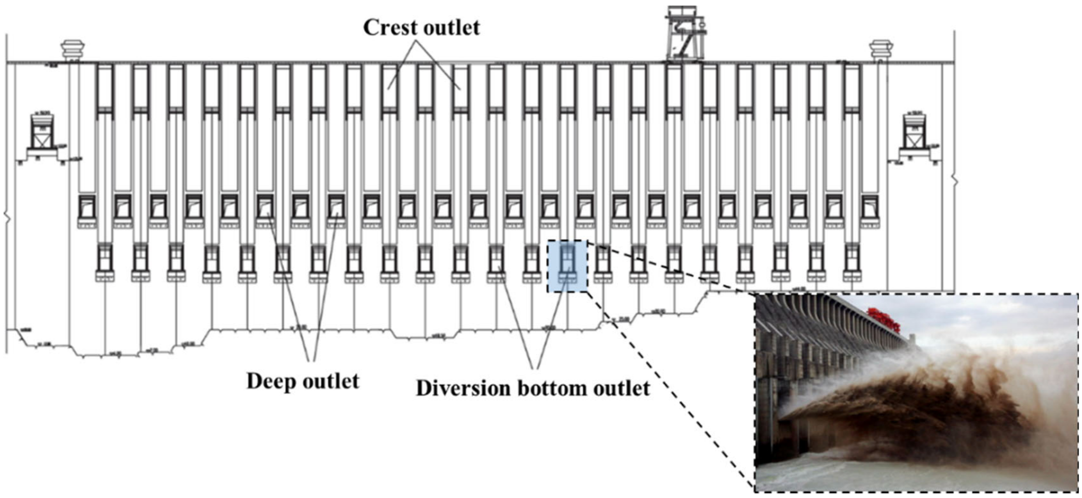


Figure 9. Layout of the three-layer orifices, [32], [33].

This innovative layout not only meets multi-purpose requirements, such as water discharge during energy production, lowering water levels when necessary, sediment release, but also significantly shortens the length of the spillway section of the dam, reduces excavation on both embankments, and saves on engineering investment.

The most important characteristic of the lower diversion outlet is its position at the monolith joints and the significant amount of sediment passing through it, thus sediment abrasion and erosion of the flow surface due to cavitation pose a serious problem. After numerous scientific studies, certain measures have been adopted. Firstly, a long pressure pipe of appropriate size has been adopted to reduce the flow at the outlets. Secondly, a concrete erosion protection slab has been placed over the joint. Finally, a sediment retention groove has been installed at the inlet.

The discharge structures of the Three Gorges Project have the features of large flood discharge, high water head, and huge discharge power. Based on the layout with staggered three-layer large discharge orifices, combined with the actual situation of a downstream energy dissipation zone, ski-jump energy dissipation with a largely differential flip bucket was used for crest outlets and deep outlets. The drop points of the water tongues are staggered in a longitudinal direction, and the scour depth is greatly reduced, [32].

2.1.4. KEY TECHNOLOGY OF THE POWER PLANT PROJECT

One of the key technological challenges of the power plant at the toe of the dam is how to select the type of intake structure to create good water intake conditions and ensure the safety of both the dam and the intake. Considering that the diameter of the intake for the power plant at the toe of the Three Gorges Dam project is large, there are several issues if the pipe is fully embedded within the body of the dam. These include weakening the dam structure, interference during the construction process, and a prolonged construction period. On the other hand, if the entire pipeline is located on the downstream surface of the gravity dam, there are issues with lateral stability, especially seismic stability for the intake with high HD values. Therefore, it is challenging to ensure the safety of the structure. A new type of intake called "shallow-buried reinforced concrete intake with steel lining at the dam crest" (short: shallow-buried pipe at the dam crest) has been proposed. In this intake, a shallow trench is pre-installed on the downstream surface of the gravity dam, with one-third of the pipe diameter buried in the trench. Steel lining and reinforced concrete bear the water load together, as shown in Fig. 10.

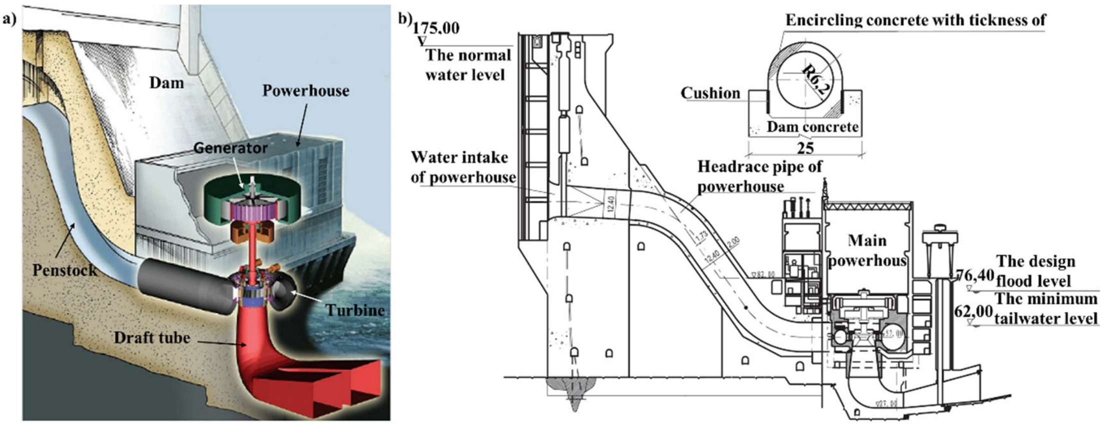


Figure 10. a) Powerhouse, [34] ; b) Schema of preset shallow slot for headrace penstock and reinforced concrete pipe with steel lining, [32].

The left power plant at the dam crest of the Three Gorges Project has been in operation for 14 years, [32]. Surveillance data for the shallow-buried intake from 2008 to 2013 show that the stress laws of the steel lining and reinforcements at the upper, lateral, and lower parts of the intake remain consistent with the design analysis.

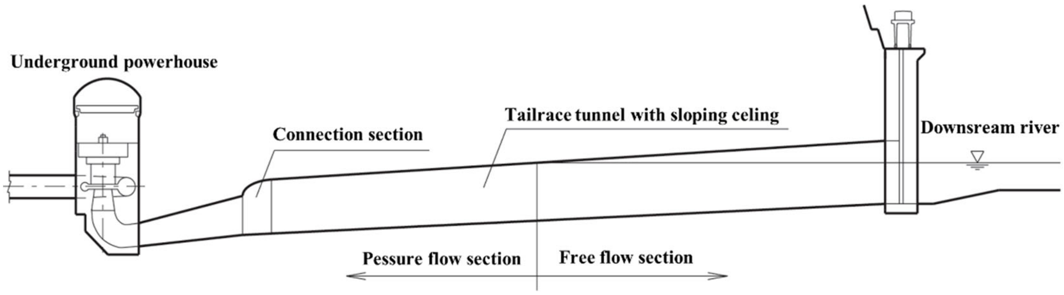


Figure 11. Schema of tailrace tunnel with sloping celing, [32].

The maximum flow of an individual unit of the underground power plant in the Three Gorges project is 991.8 m3/s, with a nominal head of 85 m. According to the traditional design method, a surge chamber of large volume should be installed. However, deep excavation of the chamber would significantly affect the stability of the surrounding rocks. Through deeper investigation of the relationship between the turbine installation elevation, the length of the pressurized drainage channel, and the downstream water level, methods such as theoretical analysis, numerical simulations, and model testing were utilized. This led to the proposal of a new type of drainage tunnel with both a free surface and pressure, termed the "drainage tunnel with an inclined ceiling".

The principle of operation of the new drainage tunnel relies on the relationship between the variation in downstream water level and the length of the pressurized tunnel section, Fig. 11. With the sloped roof, it automatically meets the vacuum degree requirement at the entrance of the drainage tunnel in case of different turbine submersion depths. When the downstream water level is low, the depth of turbine submersion is small. Consequently, the free-flowing section is long while the pressurized section is short. In this scenario, the negative pressure of water impact is minimal during the transit process, and the degree of vacuum at the entrance of the drainage tunnel meets the project standards. As the downstream water level rises, the length of the free-flowing section gradually decreases, while the length of the pressurized section increases. In this situation, the negative pressure increases, but the depth of turbine submersion gradually increases as well. Therefore, the positive and negative aspects neutralize each other to maintain a controlled degree of vacuum at the entrance of the drainage tunnel, satisfying the project standards. This indicates that this tunnel serves as a surge chamber. Considering that the surge chamber becomes unnecessary when using the inclined roof drainage tunnel technology, the layout of the underground caverns can be simplified, and the stability of the surrounding rock can be improved, [32].

2.1.5. SHIP LIFT TECHNOLOGY

The ship lift at the Three Gorges Dam is the world's largest vertical gear-based lift, Fig. 12. It has a lifting height of 113 meters, with usable space dimensions of 120x18x3,5 meters and a moving mass of approximately 15.500 tons. Four sets of rack and pinion climbing drive mechanisms of the Three Gorges ship lift are installed on the ship compartment, and four sets of accident safety mechanisms are arranged adjacent to the drive mechanism. The safety mechanism adopts the long nut column short rotating screw type, and uses the friction self-locking condition of the screw and nut trapezoidal thread to realize the safe locking of the ship's cabin. The ship chamber is the key equipment of the ship lift, and the design of other structures, equipment, and facilities is focused on the ship chamber. The self-supporting ship carrier consists of two main beams, two safety beams, two drive beams, chamber plate structure, and ship carrier head structure, as well as auxiliary structures. Both ends of the safety cross beam and the drive cross beam are suspended on the outer side of the main longitudinal beam to form the side platform structure, [35].

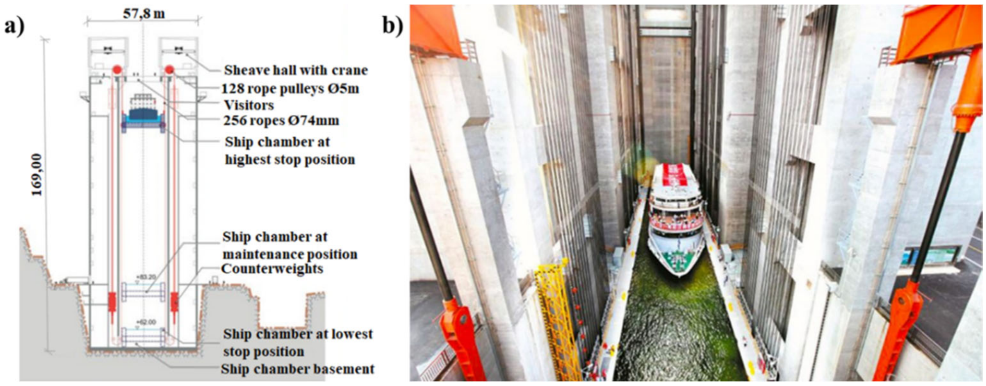


Figure 12. a) Shematic view of ship lift, [36]; b) Process of ship lifting, [37].

The lift utilizes a beam stacking scheme with the same gate slot for gate sealing and straight gate lifting. This scheme offers exceptional advantages in gate sealing reliability, equipment operation safety, as well as accommodating water level variations during navigation. The upper gate of the ship lift has 7 operational overlapping beams and 1 operational straight gate. The auxiliary water retention gate is constructed in the form of the same beam that overlaps with the slots and lifts the straight gate, located upstream of the operational gate. This gate is used for maintenance in case of accidents.

The process of a ship passing through the lift takes approximately 40 to 60 minutes in one direction, and the lift can accommodate only one ship at a time. After detaching from the gate at the upper stream, the ship vertically descends at a speed of 0,2 m/s until it reaches the same level as the other side of the dam. The lift then connects to the gate on the opposite side of the dam, after which the ship exits the lift. This operation is then repeated in the opposite direction, i.e., the second ship is raised to the upper reservoir. For safety reasons, the speed of the ship during entry and exit from the lift must not exceed 1 m/s, [38].

2.1.6. KEY TECHNOLOGY OF FIVE-STEP SHIP LOCK

Medium and large ships, weighing over 3.000 tons, must use the five-step ship lock. With a ship lock, it is possible to enable the passage of ship on both sides of the dam simultaneously, Fig. 13. The southern route is used by vessels from the upper watercourse, while the northern route is used by ships from the lower watercourse. Ships must pass through each of the 5 chambers, one after the other, in order to overcome the difference in water level. The maximum allowable speed of the ship during entry and exit from the ship lock is 1 m/s, while the maximum allowable speed between two consecutive chambers is 0,6 m/s. Compared to the ship lift, the five-step ship lock has a greater capacity, allowing the passage of four ships in each group, but the passage takes at least 2,5 hours, [38].

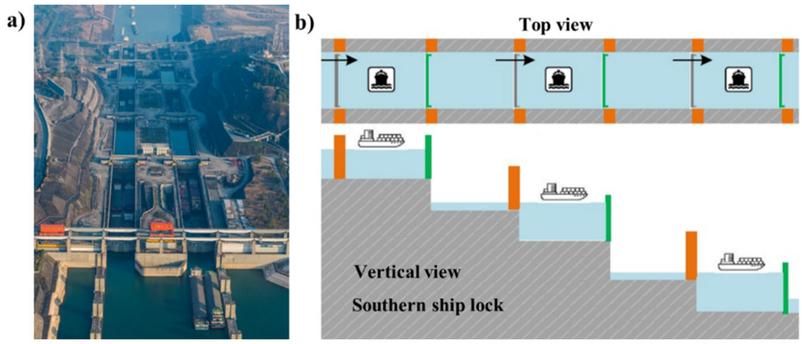


Figure 13. a) Ship lock, [39]; b) Process of passing through a ship lock, [38].

2.1.7. TECHNOLOGY FOR TRANSFERRING WATER WITH HIGH HYDROSTATIC PRESSURE AND LARGE FLOWRATES.

The dual-line continuous five-step ship lock of the Three Gorges Project represents the largest river lock in the world. The designed water level is 113 meters, with a maximum operating valve height of 45.2 meters. The one-way carrying capacity is designed as 5 x 10^7 tons, and the allowable free space height is 18 meters. The effective dimensions of each chamber are 280 meters x 34 meters x 5 meters (length x width x minimum water depth above the sill), Fig. 13.

The key technology in the hydraulic project deals with ensuring the safety of the canal system and valve gears, as well as the resting state of the chamber during the required water transfer time.

The type of water transmission system adopted in the Three Gorges Dam includes the following: The main water transport gallery is symmetrically arranged on either side of the ship locks. Separate water outlets with four segments and eight branch pipes with constant inertias are installed on the lower plate of the chamber, and water energy dissipation plugs are placed over the water outlets. Excellent dynamic balance characteristics and dual dissipation of water energy (through the cover and water cushion of the locking chamber) ensure stable and rapid water transport in the chamber.

The ship lock is located on the left bank of the dam. The main structure is 1.6 km long and is constructed within the mountain, excavating the rock mass to a maximum depth of 170 m. If a traditional gravity construction were adopted for the ship lock, the amount of excavation and concrete would be enormous, construction would take a long time, and the high slope would be extremely complex. Based on the geological conditions of the lock location, it was proposed that the lock be fully lined. For this type of ship lock, the head of the lock and the side rock chamber are lined with a thin reinforced concrete lining. This lining works together with the rock mass to withstand the loads from the gates with inclined ladders, water pressure, and ships, through specially developed high-strength shear bolts. The ship lock of the Three Gorges Dam, with its double lines and 5 steps, is the world's first fully lined ship lock, [32].

2.1.8. STABILITY OF THE FOUNDATION

The Three Gorges Dam consists of 23 spillway sections, located in the middle of the river channel with a total length of 483 meters, while 26 sections of the dam with powerhouses are located at both ends of the spillway dam, with a total length of 1.228 meters. Along the foundation line, the dam sections are built on different ground levels, low on the river bottom and high on the riverbank. Detailed geological investigations show that although the dam foundation mainly comprises plagioclase granite that is intact, homogeneous, of low permeability and high strength, there also exist weathered zones, faults and joints in the rock mass.

The dam foundation mainly consists of rock blocks, various faults, fractures, joints and so-called ‘rock bridges’ (defined as the intact rock between the ends of sub-parallel fractures). Most of the faults and joints have a steep dip angle, but there are gently downstream-dipping joints that are actually the most important factors influencing the stability of the dam. On the other hand, even in the regions where the gently dipping fractures are most developed, no deterministic and through-going sliding paths in the rock mass exist due to the presence of the rock bridges. Thus, the dam could slide only if some of the rock bridges fail, so as to create at least one throughgoing sliding path, [40].

2.2. BENEFITS

2.2.1. FLOOD CONTROL

The dam is considered an indispensable key project in controlling serious floods in the middle and lower reaches of the Yangtze River because the upper Yangtze generates flood peaks much larger than the capacity of the middle and lower reaches, especially at Jingjiang, where the land outside the embankments is lower than the level of floodwaters. In the event of an extraordinary flood, it would overflow the embankments, directly endangering 15 million people, 1.53 million hectares of arable land, and a number of large and medium-sized cities, enterprises, and vital infrastructure facilities.

That has always been a potential threat to China. With the completion of the project, a large reservoir of 39.3 billion cubic meters has been formed, of which 22.15 billion cubic meters are intended for regulating flood peaks and storing floodwater, raising the flood control capacity of the Jingjiang to the standard of a 100-year flood control, and if combined with other measures, it can prevent the occurrence of devastating floods. Therefore, the construction of the Three Gorges Dam is an important step in ensuring the safety of people and the economic development in the middle and lower reaches of the Yangtze, [27].

2.2.2. ELECTRICITY PRODUCTION

The Three Gorges Dam is an important component of China's energy program and electricity production, as well as one of the important measures in balancing the proportions of energy sources, achieving the transmission of electricity from west to east, and coordinating the arrangement of electricity supply throughout the country. The total installed capacity of the Three Gorges Dam is 18,200 MW, with an annual production of 84.7 TWh. If we add six generating units of the underground power plant and two units for supplying the power plant, the total installed capacity reaches 22,500 MW, which constituted one-tenth of the total national capacity in 1996. With this in mind, the Three Gorges Dam power plant is the leading power plant in China's electrical grid, [27].

2.2.3. NAVIGATION

The Yangtze River is considered the "golden waterway" of China, accounting for about 80% of the country's domestic inland water transport. It has always been a navigational route for Eastern, Central, and Western China. However, the navigational channel, especially the 660 km section from Yichang to Chongqing, passes through steep canyons where the water level can reach up to 120 meters, the currents are fast, and there are many dangerous rocks. The depth and width of the navigation routes are insufficient, leading to high navigation costs. The dam has fundamentally improved navigational conditions by submerging dangerous rocks, increasing the depth of navigation, calming water currents, and expanding the navigable area. This allows 10,000-ton tugboats to travel from Shanghai to Chongqing. The low navigation costs and large transport capacity have far-reaching significance in alleviating pressure on railway transport and speeding up the flow of goods between the east and west, thereby altering industrial arrangements, [27].

2.3. IMPACT ON THE ENVIRONMENT

A large portion of China's electricity is generated by thermal power plants, which burn one of the dirtiest fossil fuels - coal, and the Three Gorges Dam reduces its usage. However, there are significant ecological and geological changes in the Yangtze River basin, both upstream and downstream of the dam itself, [41].

2.3.1. EMISSIONS

The Three Gorges Dam has reduced coal consumption, which was used for electricity generation, by 31 million tons per year. This has avoided the emission of 100 million tons of greenhouse gas emissions, one million tons of dust, one million tons of sulfur dioxide, 370.000 tons of nitric oxide, 10.000 tons of carbon monoxide and a significant amount of mercury. Hydropower saves the energy needed to mine, wash, and transport the coal from northern China. Furthermore, maritime traffic has reduced carbon dioxide emissions by 10 million tons compared to truck usage, while costs have decreased by 25%, [42].

2.3.2. EROSION

Erosion and sedimentation in the area of the dam are directly linked to it. As much as 80% of the land area around the dam experiences erosion, with approximately 40 million tons of sediment deposited in the Yangtze River annually. Due to slower flow above the dam, a significant portion of this sediment is retained there instead of flowing downstream, resulting in a much lower sediment load downstream [42]. Sediments primarily accumulate during the flood season, and the operation of the reservoir at the flood control level, which is 145 meters, is favorable for sediment release. Research indicates that if the dam operates for 100 years at a level of 175 meters, the reservoir will achieve sediment balance between inflow and outflow, [27].

2.3.3. LANDSLIDES

Erosion within the reservoir, caused by rising water levels, has led to frequent landslide occurrences, resulting in disturbances on the surface of the reservoir. Two incidents occurred in May 2009 when between 20.000 and 50.000 cubic meters of material fell into the flooded Wuxia Canyon of the Wu River, [42].

3. CONCLUSION

In this paper, we investigated the emergence of the first hydraulic engineering structures. We acquainted ourselves with the four primary types of dam constructions: embankment, buttress, arch, and gravity dams, which developed in line with the requirements and technological capabilities of their times. We analyzed the fundamental structural characteristics of each type mentioned and observed how each construction is tailored to the specific terrain requirements, prioritizing stability, safety, and cost-effectiveness. Understanding these structural elements provides us with a deeper insight into the complexity of dam engineering design and enhances our understanding of their role in water management and infrastructure development.

The Three Gorges Dam represents an extraordinary engineering marvel, showcasing China's dedication to economic development. One of the most significant benefits of the Three Gorges Dam is its contribution to flood control, thereby protecting millions of people living in downstream regions and helping to reduce economic and social disruptions caused by frequent floods. Dam has also reduced fossil fuel consumption, contributing to a decrease in harmful gas emissions. Additionally, the Three Gorges Dam has improved transportation and trade along the Yangtze River. In addition to its benefits, the dam also leaves a few negative consequences. The formation of the reservoir is closely linked to erosion in the surrounding areas, leading to landslides on its banks and sediment deposition.

During the design and construction of the Three Gorges Dam, a series of challenges were continuously faced. Significant attention was devoted to the floodwater discharge system and energy dissipation during high water levels, the formation of the complex power plant structure, and the establishment of transportation routes. After detailed research, these issues were successfully overcome. A five-step ship lock and a ship lift were adopted for vessel passage over the dam, which currently holds the record as the world's largest.

The successful practice of the Three Gorges Project significantly enhances the utilization of water resources in China. Many innovative technologies developed in this project have been widely applied to future projects worldwide and play a significant role in promoting global water conservation and technological advancement in the hydroelectric industry.

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