SELECTION CRITERIA FOR DAM CONSTRUCTION METHODS

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Abstract:

Dams are one of the very important infrastructures for countries to control and benefit from its resources. These types of projects are considered mega projects for various types of characteristics like cost, constructability, resources and time. When it comes to construction methods, there is the conventional method and innovative methods. This paper covers different construction methods covering the construction of hydraulic structures in general and dams in specific. The selection criteria used to determine the best method to be used for each specific construction conditions is set. Two dams with different sizes and project conditions were studied and examined against the selection criteria in order to evaluate the validity of the applied construction method in each case.

Keywords: Dam Construction; Construction Engineering; Hydraulic Structures

1 INTRODUCTION.

The term “Dam” is a general term that generally refers to a hydraulic structure that has the primary function of impounding water by retaining it. This type of hydraulic structures can be naturally implemented or manmade. From the construction perspective the only difference between constructing a dam and constructing a barrage is the size of the job, resulting in some changes in the construction techniques (Limburg, 2006). Also, it is worth mentioning that man made dams don’t represent a modern idea, as some of the dams have been dated to B.C dates up to 3000 BC. There are many criteria used to classify the man made dams; some of them are: by referring to the size of the dam, the structure of the dam, the use of the dam or the material of the dam. Accordingly, using the classifying criterion based on the structure of the dam, dams can be classified into Arch dams, Gravity dams, Arch-gravity dams, Barrages, Buttress dams and Embankment dams (British Dam Society, 2013).

Gravity dams are given their name as gravity holds the structure to the ground stopping the water behind it from pushing it over. A cross-section through a gravity dam will usually look triangular or trapezoidal. Such structures are typically made of concrete and/or masonry, constructed across wide or narrow valleys and need to be built on sound rock to support its own weight and the large lateral hydraulic load.

From its name, an arch dam has a shape of an arch with the top of the arch pointing back into the water. An arch is a strong shape used to resist all the pushing forces coming from the water behind it. It is

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typically made of concrete and located in narrow, steep sided valleys. Arch dams need good rock for their foundations, and for the sides of the valleys, to resist the forces on the dam (British Dam Society, 2012).

On the other hand, Arch-Gravity dams constitute a combination for both the arch dam and gravity dam. It is constructed in areas with huge water flow, but with limited materials available for purely constructing a gravity dam. The lateral force that the dam is subjected to is mainly resisted by the "arch-effect" hence; the gravitation force required by the dam is lessened decreasing the need for a massive dam. This shall allow for building a thinner dam, which result in saving resources. An example of the arch gravity dam is the Hoover dam located on the borders of Nevada and Arizona (British Dam Society, 2012).

Buttress Dams are supported by triangular shaped walls, called buttresses. The buttresses are aligned apart from each other at the downstream side. Buttresses dams are developed from the idea of gravity dams; however, it uses less material due to the clear spaces between the buttresses. Such dams are also made of concrete and/or masonry, constructed across wide or narrow valleys and need to be built on sound rock to support its own weight and the large lateral hydraulic load (British Dam Society, 2012).

Embankment Dams are either earth fill or rock fill dams. Rock fill dams are mainly made from compacted rock fill, while earth fill dams are principally made of compacted earth. The materials used to construct the dams are typically excavated or quarried from nearby locations. A bank or hill is a typical cross-section for the embankment dams. Such dams have central section's called cores that are made from impermeable materials to stop the water leaking through the dam. They could be made out of soils, concrete or asphaltic concrete. Such massive dams are typically constructed in sites with wide valleys and could be built on hard rock or softer soils, as they do not exert too much pressure on their foundation (British Dam Society, 2012).

A barrage is a special kind of a dam consisting of a line of gates that can be opened or closed, according to preference in order to manage the amount of water passing the dam. According to the British dam society, "The gates are set between flanking piers which are responsible for supporting the water load, and are often used to control and stabilize water flow for irrigation systems" (British Dam Society, 2012).

Concerning dam construction methods, the different methods could be classified into "Dry methods", in which the construction site must be dry for construction to take place and "Wet methods", in which de-watering of the whole site is not needed, and construction takes place in a wet site. The four dam construction methods are the conventional in-the-dry method and three innovative methods. The three innovative alternative construction methods the Concrete-Filled Cellular Sheet Pile Cell Construction (wet method), Roller Compacted Concrete Dams (dry method) and the Float-In Method (wet method) (Spanish National Commission on Large Dams, 2012).

2 CONSTRUCTION METHODS.

2.1 Conventional (In-the-dry cofferdam construction)

In order to construct the dam in a dry environment the first step is usually done by diverting the water stream into a temporary alternative route for the water stream, this could be done by having one or more tunnel constructed using the "drill and blast" technique in which holes are drilled and explosives are put in the holes, and the broken rock is then removed after the explosion occurs. This is done until the tunnel is finished. A usual recommendation is lining the tunnels with concrete (Gerwick, 1996).

The second and third steps involve constructing two cofferdams (upstream and downstream). A cofferdam is a temporary or permanent structure constructed to maintain water out of the excavation for a permanent structure by enclosing the area around the dam. Cofferdams are usually set up so as to allow construction of the actual dam to occur in-the-dry which will create a more familiar working environment to on-land structures. The upstream one is built first in order to force the water to take the alternative route, and then the downstream one is built in order to prevent water from flowing back to the site area. Also, pumps are usually used in order to dewater any remaining or seeping water (Gerwick, 1996).

Cofferdams could be structurally classified into five different types; Braced, Earth-type, Timber crib, Double-walled sheet pile and Cellular cofferdams. The contractor usually carries out the design of cofferdams. In doing so, several factors are considered such as the sequence of construction, height, scour protection, sediment transportation, passage and stream flows, navigation (if applicable). The most commonly used material in the cofferdam construction is the sheet piles that are used within the braced, double-walled and cellular cofferdams types (Wordpress, 2012) (Gerwick, 1996).

After removing the loose rock and rubble from the site area (step four). The plinth is made, usually from concrete, and used as a foundation or connection between the dam and the valley walls and floor. Also, it offers further prevention of the leakage of water by drilling holes and pumping cement grout into cracks in the rock in the area under the plinth. The thin concrete face on the upstream side of the dam is connected to the plinth by using water stops. Finally the dam body itself is constructed in-the-dry like any typical structure (Gerwick, 1996). However, due to its massive nature (which will vary with its type and size) pouring concrete in such a project couldn't be done in one stage due to the exothermic cement hydration reactions that could delay concrete curing. Hence, concrete blocks are poured in a manner that provides interlockage and provides a mode of heat dissipation in the same time as shown in Figure 1. Utilizing the use of chilled water pipes within the blocks is a common practice in this field.

Figure 1: A cellular sheet pile cofferdam used to construct a lock in-the-dry in Nashville, Kentucky, USA (Tucker, 2012).

Although driving sheet piles is a time-consuming and effort-consuming process, using sheet pile cofferdams involves several merits. The highest benefit is the ease of construction of actual dam due to creating an easier working environment which is even safer than most of the wet techniques as the working environment is similar to on-land projects. In addition to that, no intense design considerations are required leading to faster rate of work and sheet piles are relatively easy to install and could be removed and used multiple times, hence the recycling nature of cofferdams makes them relatively more economic than other techniques (Peurifoy, Schexneydar, & Shapira, 2006).

2.2 Filled Cellular Sheet Pile Cell Construction

This is an alternative innovative wet method that doesn't require dewatering of the whole site. It is usually used to construct a big permanent cofferdam, or a small regular dam, as its advantages prevail on its limitation in such circumstances (Wordpress, 2012). The main two differences between this method and the previously discussed method is that this method is wet and the cofferdams constructed are a major part of the body of the newly constructed dam hence they could never be temporary as the conventional method (Gerwick, 1996). There are two types or shapes of cellular pile cells; circular and diaphragm (Wordpress, 2012). The cellular shape is the most common type used nowadays.

The circular type is formed of a series of circular cells (main cells) which are connected by an arrangement of piles forming a semicircle (arc cells) as shown in Figure 2. The connection between the main and arc cell is welded in the form of a Y or T junctions. The part where the main is shared with the arc cell is called the common wall (Gerwick, 1996). It consists of two main components: Main Cells or simply cells (circle-shaped) and Arc Cells or simply arcs (peanut Shaped) (Wordpress, 2012). The joint between the cell and the arc is a very tricky part that needs skilled labor and good quality control. It is usually welded using either T-junction or Y-junction (Gerwick, 1996).

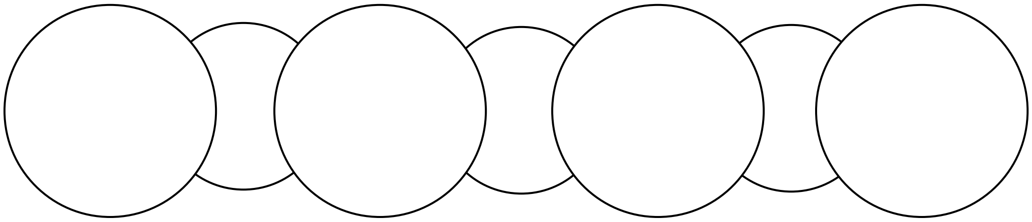


Figure 2: Circular Sheet Pile Cofferdams.

The construction sequence of such structures involves initial pre-dredging then cells that will be built simultaneously across the river are constructed using multiple reusable templates. The cells (that could be filled by concrete or sand) are constructed individually by placing the template in the preferred position in the river. The interconnecting, steel sheet piles are driven to the bedrock using vibratory hammers (Peurifoy, Schexneydar, & Shapira, 2006). In order to prepare the proper foundation for the concrete, each cell is excavated down to the rock. Then the bedrock foundation is cleaned and prepared and tremie concrete is poured through tremie pipes/tubes under water, from the bedrock up, to within 1 – 2 m of the targeted crest elevation. A concrete cell cap topping is poured on the tremie concrete. Finally, arc cells are installed to ensure the gap is filled between the main cells and the same procedures performed within the main cells are repeated for the arc cells (Gerwick, 1996).

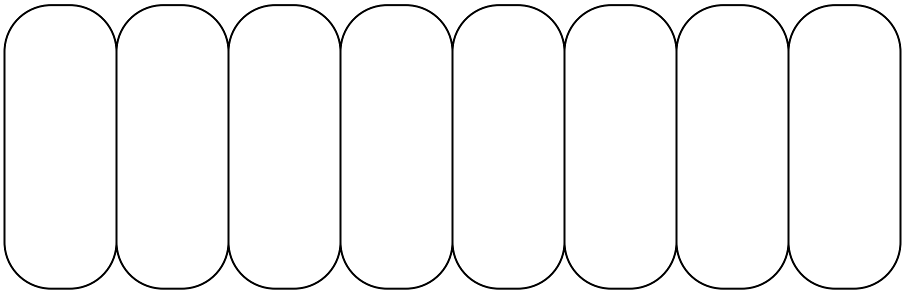


Figure 3: Diaphragm Sheet Pile Cofferdams.

On the other hand the diaphragm type is formed from a succession of diaphragm of steel sheet piles connected as shown in Figure 3. The diaphragm walls are connected together with steel piles forming arches on both sides. Cells are filled with sand, gravel or concrete after being driven to required depth. In this type, the diaphragm separating the two cells is a straight wall (Wordpress, 2012). Therefore, it is required to fill adjacent cells at roughly the same rate. If this is not performed, unbalanced pressure from the fill could disfigure the diaphragm if not designed to carry this pressure. This can result in the failure of the interlocks (Gerwick, 1996). Thus, in this case, the circular type has the upper hand above the diaphragm since in the former; it is not required to fill adjacent cells at the same time.

In general cellular cofferdams have several merits, one of them is the fact that the cells could be built simultaneously (and in any order) across the river (if sufficient resources are available), in order to reduce construction time. And as the case for sheet pile cofferdams, multiple re-usable templates can be used, resulting in cost reduction. The construction methodology results in a massive self-sustaining efficient structure which saves time as it could be the main part of the permanent dam body (depending on the dam design). Only standard marine construction equipments are needed, hence the abundance of contractors owning such equipment results in a decrease in the overall cost in addition to the fact that the materials needed are readily available. The time saving reduces the risk for the contractor, as it reduces the amount of time the section of work is exposed to the river environment. Furthermore, the overall environmental footprint during construction is reduced; accordingly, construction can be implemented without having to navigate the river during construction. However, all these merits prevail only when the right circumstances are available as such method is limited to small to medium sized dams and good quality control is needed regarding the welding procedures especially at the joints between the cells.

2.3 Roller Compacted Concrete Method

The roller compacted concrete (RCC) was developed in the 1960s mainly for applications involving high-volume concrete structures. RCC concrete mixtures differ from conventional concretes by its high percentage of the aggregates compared to the conventional concrete mixtures since RCC mixtures mainly consists of 90% aggregates and the other 10% consists simply of the Portland cement and a very low percentage of water in addition to that, pozolanic admixtures like silica fumes and fly ash are added to the mixture. The addition of pozolanic admixtures to the concrete is in order to increase the cohesiveness, lessen the permeability of the concrete and most important reduce the heat emissions produced from the cement hydration reaction. Hence, there is no need to divide the dam into inter-locking concrete blocks during forming and pouring anymore, in the matter of fact the concrete pour is done in vertical layers and compacted by compactors (ACI 207.5R-11, 2011) .

Figure 4: RCC dam construction in Ghana (Schiffler, 2014).

This method is a typical in-the-dry method in terms of needing to re-route the river, construct two cofferdams upstream and downstream of the dam location and dewater the site. What is different here from the conventional method is the method of constructing the dam body itself. The dam construction is done in layers; the methodology in general is mainly placing lifts, ranges between 0.3m to 0.7m, of RCC concrete above each other but in a sloped manner. The downstream side is the sloped side while the upstream is kept vertical as shown in Figure 4. Concrete is transported to site in large dump trucks or conveyor belts and spread using dozers to evenly spread the freshly dumped concrete to fill the formwork marked zone. Vibratory compacting rollers – commonly used in pavements – are driven over the poured layer to compact it (ACI 207.5R-11, 2011). Due to the very short setting time, the climbing formwork (typically 1m in height) should be raised up quickly and the process is repeated for the next lift. As an alternative, slipforms could be used in order to avoid wasting time in dismantling formwork and re-assembling it again. The fact that RCC has a very low slump eases the fast removal of formwork in addition to the fact that as the RCC isn’t poured in blocks like in the conventional method the amount of forms is less and the time to form and dismantle them is reduced. In between successive lifts, grout is injected in the connections to ensure no seepage or leakage would occur that potentially have disastrous consequences. Then, and when all layers have been poured and compacted, a smooth layer is added to give the dam a smooth facade and better distribute forces. Finally the cofferdams could be removed and the dam is flooded (Spanish National Commission on Large Dams, 2012).

This method saves significant costs specially in the formwork cost as it is lowered because the layer method allows for reuse of the same set of forms. In addition to that the cost of pipe cooling used in the conventional method is saved as no pipe cooling is required due to pozolanic admixtures reducing the heat of hydration. The sequence of forming, pouring and dismantling forms is significantly faster than that of the conventional method as the total project duration is almost 1-2 years less than conventional concrete dams. However, RCC could only be applied in limited types of soils as alkaline soils could induce unnecessary reactions with the pozolanic admixtures. Also producing RCC requires availability of large quantities of aggregates. In addition to that, the layer method allows for little room for error when compared to the conventional method as each layer depends structurally on the layers beneath. Hence, the compaction must be as perfect as possible especially in the lower and intermediate layers (Spanish National Commission on Large Dams, 2012).

2.4 Float-In Construction

The float-in method is a type of wet construction that allows the dam to be built in “wet” conditions. As the name suggests, segments of the dam float to the desired location and are placed alongside each other without the process of dewatering. These segments could be made of either precast concrete or prefabricated steel. In mega-projects, the float-in method could actually save huge amount of time and money as opposed to other methods (Butler, 2011).

The float-in method needs extensive planning and detailed designs. It is a difficult method to implement and only specific contractors will be able to construct a dam using the float-in method. First, the segments of either steel or concrete are assembled offshore and sent to the site. Then a launching facility is constructed at the same time dredging is carried out using dredgers or clamshells. The segments are launched to the casting basin, and then the casting basin is flooded. The segments are then towed using barges and placed in the specific locations and attached to the foundations. Lastly, the voids between the segments are filled with concrete by tremie concreting (Butler, 2011).

This method is ideal for large sized dams as it saves the cost and time of cofferdam construction. The fact that it doesn’t need the river to be rerouted during the dam construction reduces disturbance in the river trafic and also causes less environmental impacts when compared to other methods. Also, the fact that the segments are prepared in land then transported to the location allows for flexible customized dams design and allows time for terrain adjustments and leveling during foundation assembly as these operations could be done simultaneously while the segments are prepared elsewhere. However, only few contractors have the experience, special equipment and skilled labor resources enabling them to take such a job. In addition to that such a method needs extensive planning and site preparation (Ben C. Gerwick Inc., 2013) (US Army Corps of Engineers, 2013). The fact that tremie concreting is implemented forces the authorities to plan for more regular inspection, monitoring and maintenance programs to assure the structural soundness of the dam. The fact that construction and tremie concreting take place in the wet river environment is a source of risk by itself as it should be done during times/seasons of low river speed. In addition to all of that as the foundations are not constructed in a dry area, such a method is limited in use in case of soils having sufficient bearing capacities to support the dam own weight (Butler, 2011) (US Army Corps of Engineers, 2013).

3 CONSTRUCTION METHODS SELECTION CRITERIA.

Based on the discussion of the different dam construction methods presented in the previous section, a selection criteria could be developed to aid the decision making process concerning the dam construction methods. The project size, time frame, resources (whether material, labor or equipment), cost, level of risk and soil type are the main factors governing the method choice. From a project schedule perspective the float-in technique is the fastest (especially for large-scale projects) followed by the RCC method while the conventional and cellular methods are the slowest. However, this speed could be on the account of something else as the level of risk is highest in the float-in technique followed by the RCC method while the conventional and cellular methods are the least risky. From a material perspective the RCC is limited to a certain type of concrete with certain mix designs while the float-in method depends on the use of prefabricated concrete (or sometimes steel) with the aid of tremie concrete while typical conventional materials (whether concrete, sand, masonry or soils) are used when applying the conventional and cellular methods. The non-conventionality of the float-in and RCC methods is also attributed to the non-conventionality of the equipment associated with these methods in comparison with the relatively conventional equipment utilized in the other two methods. Hence, for most of cases, due to this capital intensiveness of the float-in and RCC methods, if properly designed and managed, these methods are cost saving when constructing larger dams while the other two are cost effective for small to moderate dams if properly designed and managed. Finally, the soil comes into effect due to its bearing capacity and chemical composition as for the float-in method having deep foundation is difficult to apply in wet conditions making this technique limited to soils of high bearing capacities (e.g. rock and firm clay) while the pozolanic admixtures used in the RCC could react with alkaline soils, hence it is not recommended for such soils while the other two types could be used for any soil provided the foundation system (shallow or deep) is designed properly. A summary of the selection criteria could be found in Table 1.

Table 1: Selection criteria for dam construction methods.

Construction Method	Conventional	Filled Cellular Sheet Pile	Roller Compacted Concrete	Float-In
Cost	Cost-saving for small and medium dams	Cost-saving for small and medium dams	Cost-saving for medium and large dams	Cost-saving for large dams
Risk	Low-Medium risk	Low-Medium risk	Higher risk	Highest risk
Materials	Concrete, steel, sand, gravel or soil	Concrete, steel, sand, gravel or soil	Roller Compacted Concrete	Precast Concrete or Steel and Tremie Concrete
Equipment	Simple	Simple	Requires special equipment	Requires special equipment
Labor	Semi-skilled	Semi-skilled	Skilled	Highly skilled
Construction Speed	Slowest	Medium	Medium	Fastest
Recommended Dam Size	Small – Medium	Small – Medium	Medium – Large	Large
Soil Type	Applicable for most of soils	Applicable for most of soils	Not recommended for alkaline soils	Limited to soils with high bearing capacities

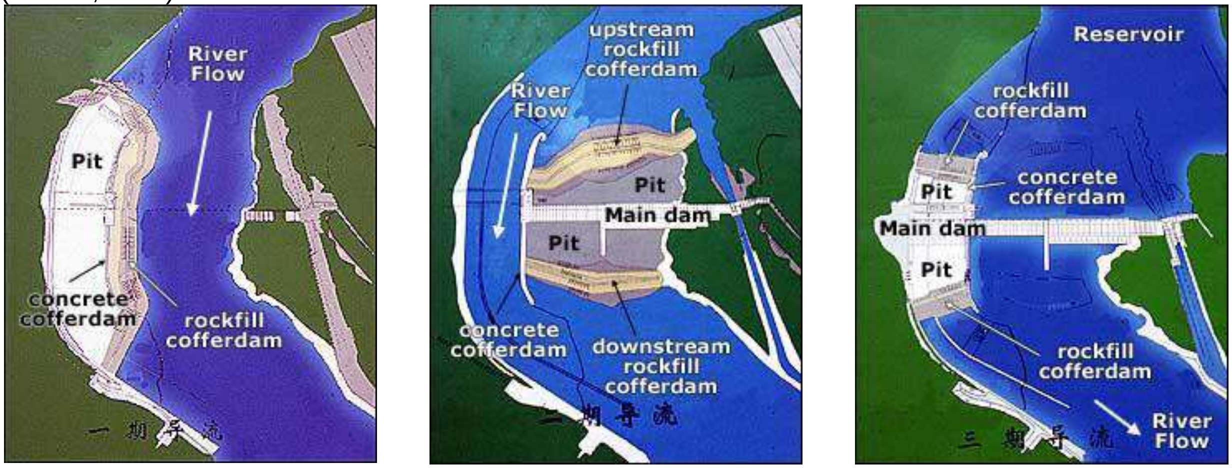
4 CASE STUDIES.

4.1 Three Gorges Dam, China

The Three Gorges Dam - built across the Yangtze River in China – is one of the largest dams in the world and the largest hydroelectric power plant built till today. It took fifteen years to build the dam and operate the hydropower station, as the construction started back in 1994 and by 2009 the construction was complete and all the equipment were being fitted and the generators started operating. This gravity dam is 2300 m long, 185 m high and its base is 115 m wide and at the top it is 40 m wide (Zhou, 2014).

4.1.1 Applied Method

This $ 22.5 billion project was divided into three main phases. However, due to the permeability and low bearing capacity of the soil beneath the river, grout was injected in the soil all over the location before the beginning of phase I. The three phases are shown in Figure 5, Figure 5a illustrates the construction of phase I in which a rock fill cofferdam (covering the upstream, side and downstream) was built on the left side of the river then water was sucked out of the river through pumps, following that, the pit was excavated to a deeper depth to sustain the flow of the river as the river was diverted to this side (left) during the next phase while the construction of the main dam was ongoing on the right side. After that a concrete cofferdam was constructed along the side of the excavated pit and then the rock fill cofferdams were destroyed allowing water to flood the pit in order to re-route the river. After the river is re-routed, phase II of construction takes place as shown in Figure 5b. Within this phase another two rock fill cofferdams were built on the right side of the river, upstream and downstream of the area where the dam was to be constructed. After dewatering, the construction of this part of the main dam commenced. Finally, within phase III, and after demolishing the cofferdams constructed in phase II, two more cofferdams are built, again on both the upstream and downstream and water is pumped out of the river to create a pit where the last part of the dam will be executed as shown in Figure 5c. Then, the last two cofferdams were demolished as the dam is ready to control the water flow (British Dam Society, 2010) (Cimino, 2013).



(a) Phase I (b) Phase II (c) Phase III

Figure 5: The Three Gorges dam construction phases (British Dam Society, 2010).

Concrete was poured in sections as described in section 2.1 as for a typical conventional dam construction method. Climbing/jump formwork were used in this project, where the whole dam was divided into sections and each section has its own formwork. This eased the process of pouring concrete as dividing the total area into smaller sections will result in less volume of concrete to be poured at a time (the same time). Also in case of problems when using this method, only the affected section will get delayed instead of delaying the whole project if it was a bulk formwork in which concrete gets poured at once. Also, as the case for any dam constructed using the conventional method, the high temperature due to the cement hydration reactions was a major issue. Thus there were certain measures that were taken to insure that the concrete temperature stays within the allowable temperatures. Ice was used in the mixing water of the concrete to cool the concrete mix temperature down. Also sprinklers were used to create a sort of virtual barrier between the temperature at which the concrete is being poured and the atmospheric temperature especially during summer seasons. The concrete temperature was continuously recorded and controlled during the production and the pouring processes either through automated systems to do so or even through quality control personnel (engineers) who measured the concrete temperature with conventional thermometers (Cimino, 2013).

4.1.2 Construction Method Evaluation

Concerning a megaproject of that size and importance, a major question could be raised about the reasons behind using the conventional method instead of using the float-in or the RCC methods that would have been expected to save a lot of time and cost for such a large scale project. The answer lies in the soil nature as the soil had a bearing capacity that wasn't sufficient enough to support the dam sections installed using the float-in technique. In addition to that, the currents within the Yangtze river are high which could cause high risks during installing prefabricated segments using the float-in technique and even if the segments would have been installed safely and properly, another problem would have occurred during pouring the tremie concrete in between the different segments due to the high water currents. Hence, the float-in technique could have never been used in this case.

On the other hand, the RCC would have been very efficient in such a project. However, another issue comes into the picture which is the chemical sensitivity of the RCC mix due to the nature of its components and whether it may react with the soil beneath or not. The available information doesn't provide sufficient data about the chemical reactivity of the soil at site or its pH. Hence, if the soil was known to be inactive it would have been a more appropriate option to use RCC in order to save time and save the cost on formwork and the hassle of cooling down the concrete and monitoring its temperature.

4.2 Braddock Dam, Pittsburgh, PA, USA

This dam that is owned by the Pittsburgh District of the U.S. Army Corps of Engineers and constructed by Ben C. Gerwick, Inc involved the application of off-site prefabrication and float-in installation of large precast concrete elements of this dam and its lock. The dam was located on the Monongahela River at Braddock, Pennsylvania, eleven miles upstream from Pittsburgh. This project had a budget of $ 107 million and took five years to complete. The dam weighed 20600 tons and measures 182 m by 32 m divided into two prefabricated segments (Ben C. Gerwick Inc., 2013).

4.2.1 Applied Method

The two dam segments were casted in a casting basin off-shore, in the mean time, foundations were installed in the site. The foundations were short piles (7.6 m deep) as a layer of hard sandstone was located at this depth. Then, the segments were launched and dragged to the fitting area as shown in Figure 6. Then the segments were placed in their exact locations on the foundations and grout was injected between the segments and the foundations and the bottom segments compartments were in-filled with concrete and while the pile tops were grouted to the segments (Ben C. Gerwick Inc., 2013) (US Army Corps of Engineers, 2013).

Figure 6: Floating the dam segments (Bittner-Shen Inc., 2013).

4.2.2 Construction Method Evaluation

This project was a typical case for a “float-in” dam construction method as all the circumstances were in favor for using such method. The fact that the sandstone layer existed at a depth that was attainable by short piles eased the use of this method as if this sandstone existed at deeper locations maybe the float-in technique wouldn’t have been the best choice to be used. Also, the presence of an old dam (that went out of service after constructing this newer one) near the location helped in controlling the water currents hence easing the process of moving the dam segments to location, the concreting and grouting process at the joints with the foundations. In addition to all of that, applying such a technique could have been very difficult if the contractor didn’t have the “know-how”, skilled personnel and proper equipment to do the job right.

5 CONCLUSIONS AND RECOMMENDATIONS.

When examining the methods applied in the two cases discussed in section 4 of this paper against the selection criteria developed in section 3, the selection criteria proved that it covered the different aspects governing the selection of the most suitable methods for different dam construction cases. However, it is highly recommended when using the selection criteria matrix to take all the factors governing the method selection into account as neglecting some of them could cause real problems.

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