Prestressed Constructions without Steel. A Project of the Spanish Engineer Eduardo Torroja

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ABSTRACT: The aim of this paper is to show the result of the research made by the Spanish engineer Eduardo Torroja focused in finding alternative ways to build prestressed structures. It presents the design of a masonry reservoir in which a precompression is made using an original method. The reservoir is made in reinforced masonry. The wall of the tank has three layers, one is a reinforced masonry, other a masonry wall and, between both, a concrete wall. This concrete wall was made by the injection of cement mortar and the hydrostatic pressure provided the stress needed in the reinforcement of the masonry. The construction system can be an economical way for built reservoirs, highly useful in poor areas. A future work, focused in improve the system, is also proposed.

INTRODUCTION

The improvement of constructions using previous tension. Some initial attempts

From the beginning of the use of reinforced concrete, it was clear that cracks appeared at the tensile side. That was a limitation for the use of the new material, and builders and engineers tried different alternatives in order to prevent these cracks from appearing since the late XIX century. In 1924, the Spanish engineer Eduardo Torroja started to work and one of his first designs was the “Puente de la Enramadilla”, a bridge in Sevilla (file nº5 and 6 of the Archivo Eduardo Torroja, AET. This file is stored in the Centro de Estudios Históricos de Obras Públicas y Urbanismo, CEHOPU, in Madrid, and can be consulted.) The design was a frame one span in reinforced concrete. To build it, a method was proposed that ensured the behaviour of the structure was as close as possible to the hypothesis set out in the design. The bridge was built as two cantilevers from each pillar and the union of both sides was made afterwards. This way, the self load the distributions of bending moments is ensured and their value is that of a cantilever. When the beam was finished, by means of the construction of the joint in the middle of the span, this ensured that the bending moments in the middle of the span were only a fraction of the bending moments caused by the live load.

After this first attempt to build reinforced structures enabling this behaviour to be as close as possible to that set out in the design, Torroja built the Tempul aqueduct near Jerez in Cádiz (AET file nº 2). In this case the beams that supported the pipes for water conduction were supported by steel wires. These wires came from an end of the beam to the other across the end of a high pillar. At the end of this pillar, some jacks allowed to stretch the wires. As a result of this process, the beams remained supported by the wires in the end position, avoiding the effects of elastic elongations of the wires. Some years afterwards, the same kind of wires was used to prestress the reinforcement of the channel of the Alloz Aqueduct (AET file nº 358). In this case, the way employed to give tension to the wires was the same as Eugène Freissynet used more than twenty years before in the construction of some hangars in France and in Algiers.

However, in the 50s, Torroja started a research focused in finding new possibilities for the use of masonry construction. His proposals or the churches built in Lérida, (Pont de Suert church and Sancti Spirit, AET files nº) need to be understood as an example of ways in which masonry could be used to build vaults without formwork. One of the results of this research was a proposal to build reservoirs in masonry. To ensure that they were wa-
terproof, a system of construction was designed. For this purpose, Torroja used the prepack system of concrete construction. The mortar was injected in a mix of gravel and water. This particular use of prepack concrete made it possible to have a compressed concrete wall.

THE HIGH RESERVOIR IN MADRID

In the building of a new water tank in the “Junta de Energía Nuclear” site, Torroja proposed a new system to produce watertight tanks. It was a masonry work in which the wall of the tank was formed by three layers, two made of bricks and a concrete one in the middle. The external layer was reinforced with steel bars commonly used in reinforced concrete works. These bars were in tension as a consequence of the form of building and therefore the internal part in concrete was compressed. The project was finished in 1957 and was built between April and September 1958. The water tank was in use until the early seventies and was then replaced by a reinforced concrete water tank.

Design description

The project is a 100m³ tank situated 14.00 m above the ground. The design is a 19.175 cone trunk with a diameter of 4.00m in the base and 9.20 m in the masonry made top. All the work is built in bricks of different thickness with some reinforced concrete walls. The deposit reservoir is situated 13.90 m above the ground. The construction has three parts: the internal shaft for maintenance, the external wall and the deposit itself.

The maintenance shaft is a cylinder with an internal diameter of 2.00m and 17.575 m high built in 1 ft clay masonry units. It is used for maintenance and as support of the reinforced concrete shell of the bottom of the deposit. This masonry is not reinforced. The external wall is a masonry work built with bricks 1.5ft thick with a height of 2.60m from base to top. After this height the thickness of the bricks is 1 ft. This wall is reinforced with perimetral reinforcement placed at different levels. At 14.365 above the ground, this inclined wall is the support of the external ring of the shell that made the bottom of the tank.

The tank itself is based on the above mentioned elements, the maintenance shaft and the inclined wall. The external wall is a continuation of the external wall. The tank has three parts as well: the bottom, the external wall and the cover. The bottom of the tank is a toric surface built with reinforced concrete supported by two rings. The internal ring is placed in the maintenance shaft and the external one over the external wall. The tank’s external part is formed by a wall that follows the shape of the external wall. This wall has three layers, two of them in masonry and between them is one non reinforced concrete shell 20cm thick. The external layer

Figure 1: Left, a view of the reservoir now. Middle, a cross section of the building, the disposition of the internal maintenance chimney and the external wall can be seen. Right, a detail of the section of the reservoir wall. The three layers of the wall can be seen, the external section with the reinforcement, the interior wall without reinforcement and the intermediate chamber with prepack concrete.
made with 1 ft thick solid bricks is reinforced with a 120MP elastic limit steel reinforcement. The internal layer is made of non-reinforced 0.5 ft solid brick. The 1.5cm thick cavity formed between the two layers is filled with prepack concrete. The cover is a dome 7.955m in span, supported by the two internal layers of the tank, built using a three layer brick vault reinforced by steel mesh bars. The principle of the pre-stressing system is explained by the design and is based in the use of the prepack system. This is a system of built reinforced concrete works that consists basically of putting the aggregates in place and then injecting a light expansive mortar under pressure.

The construction system

Once the foundation is finished, there is a platform to start building the masonry. The internal shaft and the external wall are erected at the same time. The external wall is defined in such a way that it is necessary to increase the number of bricks every four rows to increase the diameter. At defined heights it is necessary to include the specified reinforcements. These two masonry works continue to the height where the bottom of the tanks is supported. At this level are placed the limiting rings that define the vault of the tank’s bottom.

To build the slab in the bottom it is possible to use as a formwork a brick vault with the appropriate shape built with tile bricks. This makes it possible to avoid the use of scaffolds and formwork required to build a concrete shell. Torroja had used this system to build the bottom of the Fedala’s water tank (Morocco 1955). Once the bottom is built, it is possible to build the walls of the tank.

The construction of the tank requires two steps. On the one hand, the construction of the internal shaft continues to the defined height using a 1 ft non-reinforced masonry wall. On the other hand, the external layer has the same shape as the part below the tank, but has more reinforcement in each row. Once this external layer is finished, it is necessary to start the internal layer, which will have the same shape. In this step it is necessary to take care to prevent mortar or other waste from falling in the cavity between the two layers. At the same time the cavity is filled up with selected gravel. It must be clean gravel with a particle size distribution adequate to the intended concrete. It is also necessary to let some pipes in the cavity so that it may be filled up with the mortar later on.

Figure 2: The construction process is showed from left to right. First, the brickwork of the chimney and the external wall support the bottom, then the brick walls are finished; the three layer reservoir wall is made building the internal masonry wall and filling the cavity with gravel; next, the reservoir and the cavity are filled with water and, finally, the mortar is injected.

Once the two brick layer is finished and the gravel is in place, the tank and the intermediate cavity are filled up with water. In this way, the hydrostatic pressure produces a compression in the internal wall of the tank and the maintenance shaft. This compression decreases from the bottom to the water level. This pressure produces a tension in the external wall that can produce cracks and therefore some leaking. In order to maintain the pressure in the reservoir walls, more water is added as required replacing the loss. The external wall is enlarged, so that the steel bars reinforcement is enlarged elastically. This means an increase in the diameter of the wall.

At this point of the construction, with the tank filled up with water and the cavity filled up with water and gravel, it is possible to finish the construction of the wall of the tank. To do so, it is necessary to inject the mortar in the cavity from the bottom to the top using the pipes left in the cavity during its construction. The injection is done in an orderly manner, starting in one pipe until the fill reaches the end of the two adjacent pipes. Afterwards, the injection starts in these two pipes until the fill reaches the next set of pipes. This way rings of concrete are produced, taking care that the height of fresh concrete does not surpass a determined value. Once the cavity is filled up with concrete, a reinforced concrete rib is built. This rib combines the concrete cavity and the internal brick layer that is the support for the cover.

The cover is built to finish the deposit. The cover consists of a three layer reinforced brick vault, which can be built without falsework using the technique of the timbrel vault.

How the reservoir walls works

The system is based on the means used to inject the mortar in the cavity. When the mortar is injected in the cavity, it produces an increase in the hydrostatic pressure acting on the walls of the cavity. This is due to the higher density of the mortar in relation to water. The pressure over the internal wall is in balance with the hydro-
static pressure of the water in the tank. But the increase in pressure over the external wall produces an increase in the tensile strength over the masonry wall. This produces an increase in the cracking and an enlargement of the reinforcement; therefore, the diameter of the parallels is increased. The mortar injected should have little shrinkage or even be slightly expansive and the setting time should be relatively fast. The estimated time for the mortar to start setting is three hours after injection. This way the hydrostatic pressure causing the second enlargement of the reinforcement disappears. Hence the reinforcement tries to recover reducing its length. This shortening produces a centripetal pressure that compresses the intermediate concrete layer. The process of injection is continuous: this compression starts at the bottom of the tank and finishes in the upper part three hours after the end of the injection.

It is necessary to define the way the concrete is injected to determine the setting time of the mortar. Furthermore, in order to determine the reinforcement of the external layer, it is necessary to assume a certain height of non set mortar. In the calculation, an injection height of 2.50 m was considered, even if the specifications did not allow the use of more than 2.00m. These two points define the construction process because they fix the injection speed at 1.00m injection height per 1.5 hours. The maintenance shaft and the external wall up to the deposit level work on compression. The bottom of the deposit is a reinforced concrete slab designed in such a way that its generatrix is the loads and hydrostatic anti funicular pressure. This way the slab is compressed in all its sections. In the external part, there are two horizontal reactions that in the case of the internal support over the shaft produce a compression of the support ring. In the external support, the ring over the wall of the external wall is in tension.

In relation to the deposit walls, the internal one formed by the maintenance shaft is compressed all along its height, and in the external one, the concrete layer is always compressed because the pressure produced by the stored water will never be higher than the centripetal pressure produced by the reinforcement of the external wall layer.

The actual reservoir

The reservoir was built between April and September 1958 and some spots caused by the water can be seen in the images taken when the reservoir was finished. These spots were placed at the start of the reservoir wall, at the height where the bottom of the reservoir joined the external wall. The construction process made it possible for some water to pour down across the cracks that appear in the masonry wall. However, when the concrete wall was finished, the tension of the reinforcement placed in the masonry wall ensured that the construction was waterproof.

However, some things did not work properly because the reservoir was replaced by another prestressed concrete reservoir built in the seventies.

Figure 3: Left, a view of the reservoir shortly after being finished. Spots caused by water can be seen. This happened mainly at the level where the bottom of the reservoir joined the external wall. The image on the right shows how the union between the external wall and the bottom of the reservoir was made.

Improvements included in following designs

After the project was finished and in the following years, Torroja made some designs for reservoirs using this system. These proposals were presented in several competitions in France and Morocco, but none of them were built. In these new designs some changes were made. The details changed from the first design can give us some clues about the things that Torroja thought did not work properly. We can focus our attention on the changes in the wall of the reservoir.
The vault that forms the bottom of the reservoir has the shape of a torus. The directrix has the direction of the funicular of the loads acting on it. This way, at the bottom end on the ring placed in the chimney, the thrust compresses the reinforced concrete ring; but on the other border, on the external wall, the thrust pushes against the external wall. The reinforcement does not prevent some cracks from appearing. The way used to equilibrate the thrust of the bottom vault was the design of a system of tie bars. These tie bars were made in steel and laid out as shown in fig.4. This way the ring that supports the reservoir wall can be put in compression. In that ring, another change can be seen in bottom right picture of fig.4. The external wall of the reservoir joint, the ring and the external brick wall and the concrete of the cavity are connected with the shell of the bottom by some steel bars of reinforcement. The new layout, with the tie bars and with the connection between the bottom and the wall, improves the solution of the joint.

Finally, a new layout of the steel bars reinforcement can be seen in the top left image of fig.4. In the first solution the bars were placed between two bricks. The space was too short and it was difficult for the mortar to cover the bars. Therefore, protection against corrosion could not be guaranteed. Also, this layout does not ensure a good transmission of the compressive effect against the concrete wall. Instead of this layout in following designs a new organisation of brick and reinforcement is proposed. The steel bars are now well covered with mortar and the brick placed vertically act as a ring which is compressing the concrete layer of the reservoir wall.

Figure 4: Top right we can see how the reinforcement was used in the reservoir built and top left, the change in the layout of the reinforcement; the mortar protects the reinforcement in the new proposal better than in the first. Bottom left shows the system used to compress the external ring that limited the concrete shell of the bottom of the reservoir; bottom right image shows the new proposal for the start of the reservoir wall, where a reinforcement crosses the concrete layer and fits the external brick layer.

**FUTURE WORK**

The reservoir is no longer in use but it can be visited and research will start in the next weeks. This research has two main objectives. One is to describe the real state of the building, verify its dimensions, check how the concrete of the wall was built, describe its mechanical qualities and also find where the construction failed. The second is to check the tensional state of the reservoir wall. Verifying if the concrete wall is now compressed and to what extent and if the reinforcement in the masonry wall is in tension or otherwise. This research is supported by CEHOPU. Furthermore, an improvement of the construction process will be proposed. The final aim of this research is to define a system of construction that may allow to build a reservoir at a low cost.
CONCLUSIONS

After the documental research, we can say that the system used by Torroja is absolutely original. The fact that Torroja proposed this system for some reservoirs designed after the Madrid reservoir was built, prove the confidence that Torroja placed in it. Is an economical and simple way for building a reservoir. Only simple a simple masonry is needed and the most complex operation is the mortar injection.

After the construction of the Madrid reservoir, any reference has been found about the use of a similar system. After ten years in use, some crack appeared and a new reservoir was built. From 1970 the reservoir is not in use. Cracks appeared and the waterproof disappeared.

The research proposed try to found the reason of the failure and, also, propose some repairs.

The aim of Torroja was to design a reservoir which did not require using expensive methods. The use of masonry for building reservoirs is an economical way to construct this kind of buildings and its use will make it possible to built water supply facilities in rural areas with little economic resources. Torroja started his research with the construction of the reservoir in Madrid. The process of construction showed some aspects than can be improved and said improvements were introduced in his next proposals.

REFERENCES


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