THE FEASIBILITY OF PRE-STRESSED CONCRETE (PC) WATER RETAINING STRUCTURES OVER CONVENTIONAL REINFORCED CONCRETE (RC) WATER TANKS

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***Abstract*— Concrete water tanks are used to store and supply safe drinking water and**

are designed as crack-free structures. As demand for water tanks will continue to increase in the coming years, quick construction methods and economical design approaches will be helpful in the selection of water tanks for relevant applications. PC will be a better alternative for RC water tanks which are commonly used in Sri Lanka. In this paper, design guidance for PC circular water tanks resting on the ground is presented. Economic feasibility of both PC and RC tanks are compared for different tank capacities. The design and construction approaches for PC circular water tanks were identified following BS 8110-1: 1985 and BS 8007: 1987 standards. The Midas Gen finite element software was used to analyze the tanks. The design outputs were converted into structural drawings and bill of quantities. Results of the material take-offs showed that RC is economical only for 4000 m3 or less capacity. For higher capacities (above 4500 m3), PC tanks become cheaper by around 12-14%. The information presented in this paper will therefore be helpful to understand the design philosophy for the safe and economic design of water tanks with better crack control.

Keywords*— *Circular water tanks, Prestressed concrete, Reinforced concrete, Economic feasibility, Tank capacity

I. INTRODUCTION

Water is considered the source of living for every creation, as it is a crucial element for healthy living. A Safe and adequate supply of potable water is one of the basic elements for the human to sustain a healthy life. High demand for safe and clean water is rising day by day as one cannot live without water. Thus, it becomes necessary to store water, water is stored generally in concrete water tanks and later on, it is pumped to different areas to serve the community.

Water tanks may be made of masonry, steel, reinforced concrete (RC) & pre-stressed concrete (PC). Concrete is generally the most common material of construction and when correctly designed and constructed, will provide long life and low maintenance cost. It is important to carry out both the design and construction of water retaining structures properly, otherwise, it would not give the intended service. Water tanks must be designed so that liquid is not allowed to leak or percolate through the concrete structure during the life of the structure. Crack control is more critical than strength considerations. Ground movements leading to displacement and cracking of liquid retaining structures may cause severe leakage [1]. And also the severe corrosion due to aggressive exposure conditions resulting from the applications of certain treatment [2], cracking in water tank due to restrained shrinkage & heat of hydration are the main defects of water retaining structures. Therefore, prestressing is the superior choice for crack controlling and other defects. PC structures have a lot of advantages over conventional cast-in-situ reinforced concrete structures in water supply systems. They can be designed for zero cracks, hence no leakages. No limitations for the depth of the structures require less land area, short construction period, high durability and less maintenance cost, and higher resistance to earthquakes and Tsunami situations are several advantages of PC structures compared to those made out of RC. Hoop tension on the shell due to the internal pressure is always the main problem in the cylindrical tank analysis and construction. To reduce the hoop tension, prestressing is usually used at the construction site. Pre-stressed concrete is the most efficient material for water tanks and coupled with the circular shape, they can eliminate all stress conditions. By placing the steel of the pre-stressed strands in tension and the concrete in compression, both materials are in an ideal state and the loads are uniformly distributed around the tank circumference.

The main aim of this study is to reduce the cost per unit storage volume of water. By implementing cost-effective methods in all related activities of water storage, storage cost reduction will be possible. The research studies of each component of the water supply system may tend to produce a high capacity of water storage with minimum cost. In this way, a comparative design study of PC design against RC design would control the excessive material usage.

The importance of water storage tanks is increasing due to a lack of safe & healthy water distribution. The World Bank has estimated that, out of the 85% of Sri Lanka's population living in rural areas, only 10% have access to treated tap water, and hence about 20% of the population relies on unprotected water sources for drinking [3]. The PC techniques have been widely used in Sri Lanka for various structures in 1960 – 1970s. But now PC is not much used in Sri Lanka due to lack of design knowledge, lack of construction technology & lack of skilled experienced personnel, etc. A smaller number of PC water retaining structures have been constructed. But This new technology will support to cater the ever-increasing demand for pipe-borne water in the country as it has definite advantages over conventional cast-in-situ concrete. By only using the RC design for liquid retaining structures, it is difficult to achieve high capacity while ensuring economy and durability. The post-tensioned PC design, therefore, needs to apply for liquid-containing structures for high capacity and durability.

This research develops and applies a FEM-based procedure to study the behavior of PC & RC water tanks separately. The FEM-based design procedure developed in this research could be used to complement and supplement the existing design methodology for PC water retaining structures. A literature survey has been conducted to investigate the construction technologies of circumferential prestressing that are applicable for the Sri Lankan context.

II. LITERATURE SURVEY

Some important findings from the past research regarding the RC and PC water tank design aspects & construction methods are discussed in this section.

A. Types of storage tanks

In general, the following types of tanks are used for water storage in water supply schemes.

I. Rectangular tank
II. Circular water tank
III. Intze type water tank
IV. Conical water tank
V. Spherical water tank
VI. Circular tanks with conical bottom

Bhandari, Karan Deep Singh [4] presented the economic design of water tanks with different shapes for different capacities. They considered overhead water tanks having three different shapes (square, rectangular and circular) for three different capacities (100 m^3, 150 m^3, 200 m^3). The cost of the tanks was determined by accounting for the cost of the material and formwork. Each water tank was designed using the Limit State method and then the crack width was checked by serviceability limit state IS 3370 (2009). The results have been presented in the form of graphs and tables and it has been observed that circular-shaped tanks consumed less material compared to square and rectangular ones. The amount of formwork required for a circular tank is also less than that for square and rectangular tanks thereby giving circular-shaped tanks a more favorable selection over the rectangular and square-shaped tanks.

B. Design approaches

When designing liquid retaining structures, both ultimate limit state (ULS) and serviceability limit state (SLS) conditions have to be considered. At the ULS, it is required to see whether different elements of the structure can withstand the anticipated designed loads with the legitimate factor of safety. At the SLS, the behavior of the structure under service condition has to be examined by accounting for the crack width, durability, and deflection limits. This study followed the combination of both limit states.

British Standards BS 8007:1987 has been widely used in Sri Lanka for the design of water retaining structures. In terms of circular tanks, direct or hoop tension in the circumferential direction is the governing force, which determines the circumferential prestressed reinforcement or non-prestressed reinforcement in the tank. Likewise, the vertical bending moment in a circular tank wall is another parameter which has to be assessed when determining the reinforcement (whether prestressed or non-prestressed) in the vertical direction.

Based on the information presented in the design code and the literature, following design considerations were used in this study. The maximum jacking force in circumferential strands or tendons was limited to 75% of their characteristic strength. The maximum principal compressive stress in the concrete was limited to 33% of its characteristic strength. If the flexural stress due to induced vertical bending moment by circumferential stressing operation is 1.0 MPa, the vertical prestress should be applied or circumferential prestress should be developed in several stages. When the tank is full of water, there should be no resultant tension in the concrete in the circumferential direction, after allowing for all the losses of prestressing, assuming that the top and bottom edges of the wall are free of all restraints. The maximum allowable tensile stress in the concrete from the vertical bending moment is 1.0 MPa. If the tank is empty, no tension is allowed at all for concrete.

Part 3 of Eurocode 2 contains supplementary clauses to those in Part 1 for the design of reinforced concrete or prestressed concrete for the containment of liquids or granular solids. For the ultimate limit state for the tank design, the partial safety factor 1.2 may be used for the loads from the stored liquid when the tank is full. The partial safety factor is 1.0 during the testing at the maximum liquid level and for accidental design situations. Section EC2 Part 3 for the cracking under serviceability limit state, classifies liquid retaining structures as tightness classes 0 to 3 based on leakage of small quantities of liquids and gasses by diffusion through concrete. The class zero leakage is acceptable, but class 1 leakage should be limited to a small amount by controlling the crack width. For the class 2 leakage, it is necessary to install liners or water bars to avoid the passage through the full thickness of the section. The class 3 leakage is not permitted so generally, special measures such as liners or prestress will be required to ensure water tightness. The guidance is provided to control cracking without direct calculation alternatively by arranging the size and spacing of the reinforcement bars as well. Where there is no vertical prestressing, vertical (or inclined) reinforcement should be provided based on reinforced concrete design.

The ACI 344 reports are based on the philosophy of maintaining the concrete in compression. With this fully prestressed philosophy, concrete tensile stresses are prevented under normal service loads. In general, the residual compressive stress of 1.38 MPa (200 psi) is required in the hoop direction under service load. This prevents the formation of cracks due to direct tension. Tensile stresses due to thermal and moisture gradients are not precisely estimated. The nominal residual compression is increased to 2.8 MPa (400 psi). As a result of the full prestressing principle, non-prestressed reinforcement and additional concrete wall thickness are ineffective in the structure. The tensile stresses in the tank wall due to vertical bending moment are resisted by prestressed reinforcement vertically or non-prestressed reinforcement vertically or a combination of both reinforcements. For vertical prestressing, ACI 344 requires a minimum vertical compressive stress of 1.38 MPa due to prestressing after all losses.

The Portland Cement Association (PCA) produced reports to supplement for design and analysis of rectangular and circular tanks. ACI 350 also contains several recommendations of PCA. The determination of minimum wall thickness for circular tanks is the vital difference in the PCA documents. PCA recommends that the wall thickness should be in the hoop direction, the wall does not crack under normal service loads. PCA includes an explicit allowance for concrete shrinkage in the calculations.

C. Prestressed Concrete (PC) water tanks

With the development of high-strength steel wires, engineers began to apply the same “hoops around a barrel” principle to the circumferential compression of concrete liquid retaining tanks for three reasons:

1. **Crack resistance**: By keeping concrete subjected to tension in compression, cracks are minimized or eliminated. Concrete cracking and the resulting leakage due to hoop tension from outward hydraulic forces of non-prestressed concrete water-retaining structures has been a problem for engineers for many years.
2. **Durability**: Concrete has demonstrated long-term durability in environments with constant exposure to water, wastewater, and other liquids.
3. **Cost savings and sustainability**: Because prestressing uses concrete in compression and steel in tension better, prestressed concrete tanks require fewer materials (40% less concrete and 60% less steel) than their equivalent RC tanks. Fewer material result in significant cost savings. The PC tank of 3000 m^3 or more will be cheaper than the RC tank. However, when the PC tanks which are smaller than 3000 m^3 are constructed on a highland and hillside, the amount of earthwork and site area will be reduced, as a result, it will be more economical [5].

D. Circumferential prestressing

PC is the most efficient material for water tanks, coupled with the circular shape, which minimizes all stress conditions. A section of a typical PC tank is shown in Fig.1 [6].

The prestressing cables are laid inside the wall, and they are taken out in some places of walls, where they have to be anchored properly. After the strands are stressed using hydraulic jacks at the anchorage points, concrete is poured. During the prestressing, prestress force losses due to friction. To reduce that effect, prestressing can be done over sectors of the circumference. For the anchorage of the tendons, Buttresses are provided [7]. Fig. 2 shows the use of buttresses along the circumference.

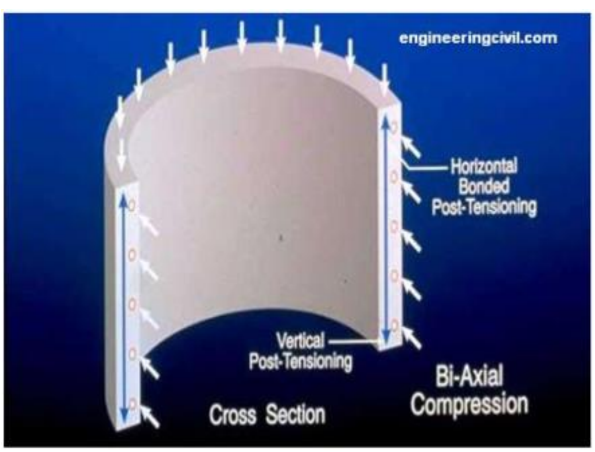

Fig. 1. Cross section of Cylindrical PC tank [6]

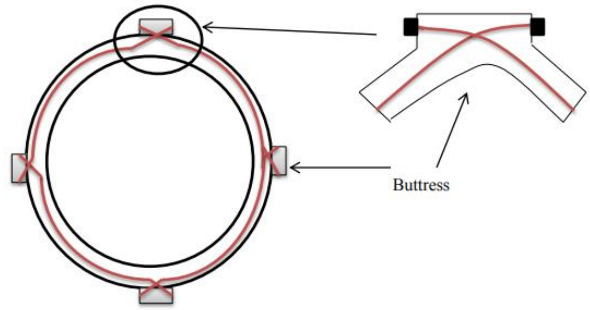

Fig. 2. Use of buttress in circumferential prestressing

Fig. 3 shows the strand arrangement of the water tank wall. In general terms, in order to reduce the effects of elastic deformation of the concrete, it is prudent to initially apply only 25 % of the total force to all the cables in the following order:

strands no. 1 - 4 - 7 - 10 - ......

strands no. 2 - 5 - 8 - 11 - …….

strands no. 3 - 6 - 9 - 12 - ......

The stressing operation can then be repeated in three further increments of 25 % until the strands are fully stressed. The amount of 'pull-in' of the cable at the anchorage point can be measured and allowed for so that losses due to this effect are zero. It is preferable to use two jacks when stressing from a buttress since the frictional losses due to curvature are reduced by this approach.

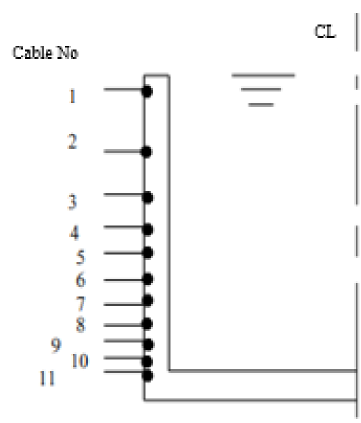

Fig. 3. strand arrangement for stressing

E. Base conditions

Circumferential precompression cannot be achieved if the prestress is applied in tanks with fixed and pinned conditions at the base, where the radial, and hence circumferential strain cannot be developed. Consequently, it has been common practice to stress some or all of the circumferential cables with the wall free to slide radially, and then pin the base to improve performance under fluid pressure [9].

III. METHODOLOGY

As the first step of the research, a comprehensive literature survey was conducted to investigate the design approaches and construction methods. Then, an industrial survey was conducted to investigate the current practices for PC water tank design and identify the defects of the existing water retaining structures. A questionnaire was carried out to collect the information from design engineers. Water tanks with six different capacities were treated in this study. The finite element (FE) models were developed using Midas-Gen software separately for both RC and PC circular tanks with different capacities. The FE analysis results were used for both design approaches after verification. The design work was conducted with the assistance of MS EXCEL programming by iterating until the optimum output was obtained. All the design results were converted into drawings. Then, a bill of quantity of each tank for each design approach was prepared to conduct the cost comparison. All BOQ were prepared using the rates given by NWSDB and BSR 2019. The reinforcement quantity and the prestressing strands quantity were determined using the drawings that were developed by Revit Architecture software.

IV. RESULTS

The results obtained from the Questionnaire Survey and the FE analysis are discussed in the following sections.

A. Questionnaire survey

The main purpose of carrying this survey is to investigate the applicability of using PC in the design of water retaining structurers instead of RC which is commonly used in Sri Lanka. This questionnaire survey has been conducted among the design engineers in the country and a summary of their comments are presented in Fig. 4 and Fig. 5.

According to the results of questionnaire survey presented in Fig. 4, main restrictions to use PC water tanks in Sri Lanka are lack of construction technology and lack of design knowledge. Most of the expertise suggestion to promote PC water tanks in Sri Lanka is the preparation of design guidelines.

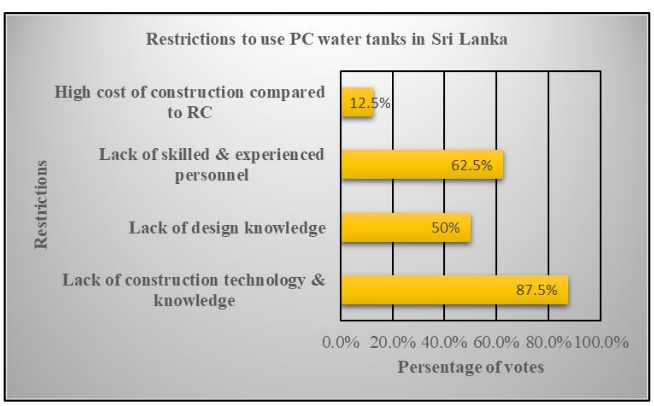

Fig. 4. Summarized results of question 1

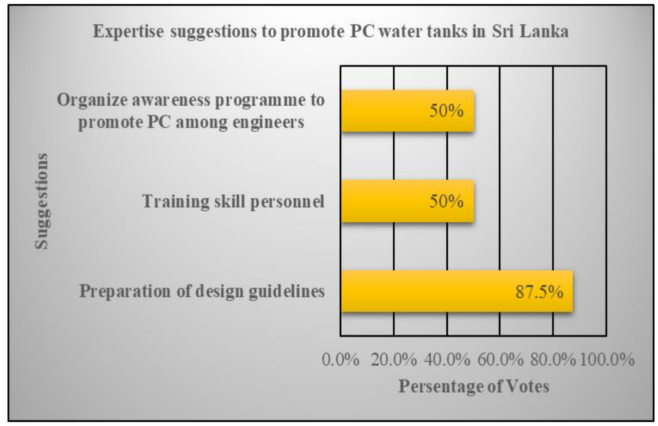

Fig. 5. Summarized results of question 2

B. Finite Element Analysis

The thicknesses of both walls and floors in water tanks are small compared to their in-plane dimensions, and hence they were modeled with two-dimensional (2D) shell elements. The static analysis was carried out to investigate their behavior under hydrostatic pressure. The water tanks were modeled with suitable dimensions for the required capacity and elevation height using the Midas Gen structural analysis software as shown in Fig. 6. Then self-weight of the elements was taken as dead load and water pressure was taken into the account as a live load. After assigning the boundary conditions, the whole structure was analyzed by accounting for both ULS and SLS loading cases.

The variation of ring tension in the wall with the height of the tank under SLS condition is illustrated in Fig. 7.

The results obtained from the Midas Gen software for ring tension were compared with those presented in the PCA tables for circular tanks and those are summarized in Table 1. It is evident that the results obtained from the FE analysis are agreed well with those presented in the PCA tables, though they slightly underestimate the values

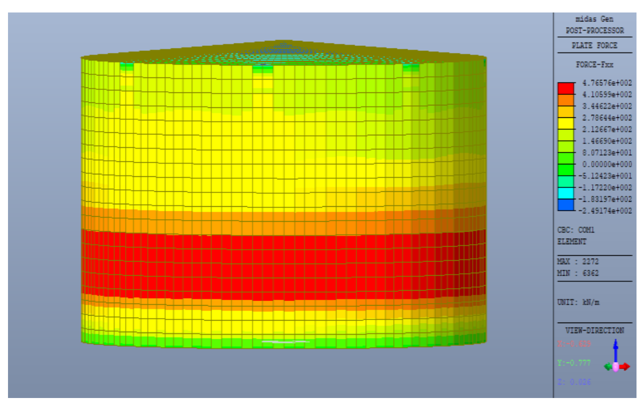

Fig. 6. 3D FE model of a circular water tank

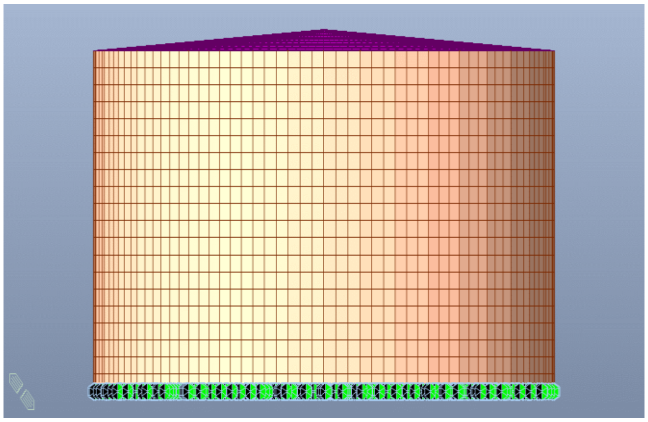

Fig. 7. Ring forces at SLS

TABLE 1. RING TENSION OF TANK WALL ALONG WITH THE WALL HEIGHT

Depth	Ring tension (kN/m)		Difference (%)
	From FEM analysis	From PCA table 9.29(a)	
1	66	76	13
2	158	162	2.5
3	234	244	4.1
4	347	334	3.7
5	435	419	-3.8
6	424	415	-2.2
7	229	244	6.1
8	110	135	18.5

C. The prestressed concrete design approach of circular water tank

The flowchart in Fig. 8 describes the PC design approach for circular tank walls as per BS 8110-1:1985 and BS 8007: 1987. The maximum design force of the strand or tendon was evaluated by considering the friction loss and other possible losses. The dimensional requirement of the concrete section was determined as per clause 4.3 (c) of BS 8007: 1987 to apply the prestress.

Designers have to follow the above steps to use the guidance. The characteristic values of high strength low relaxation prestressing strands can be obtained from BS 5896: 2012. Prestress losses can be estimated using clauses 4.8 & 4.9 of BS 8110-1:1985.

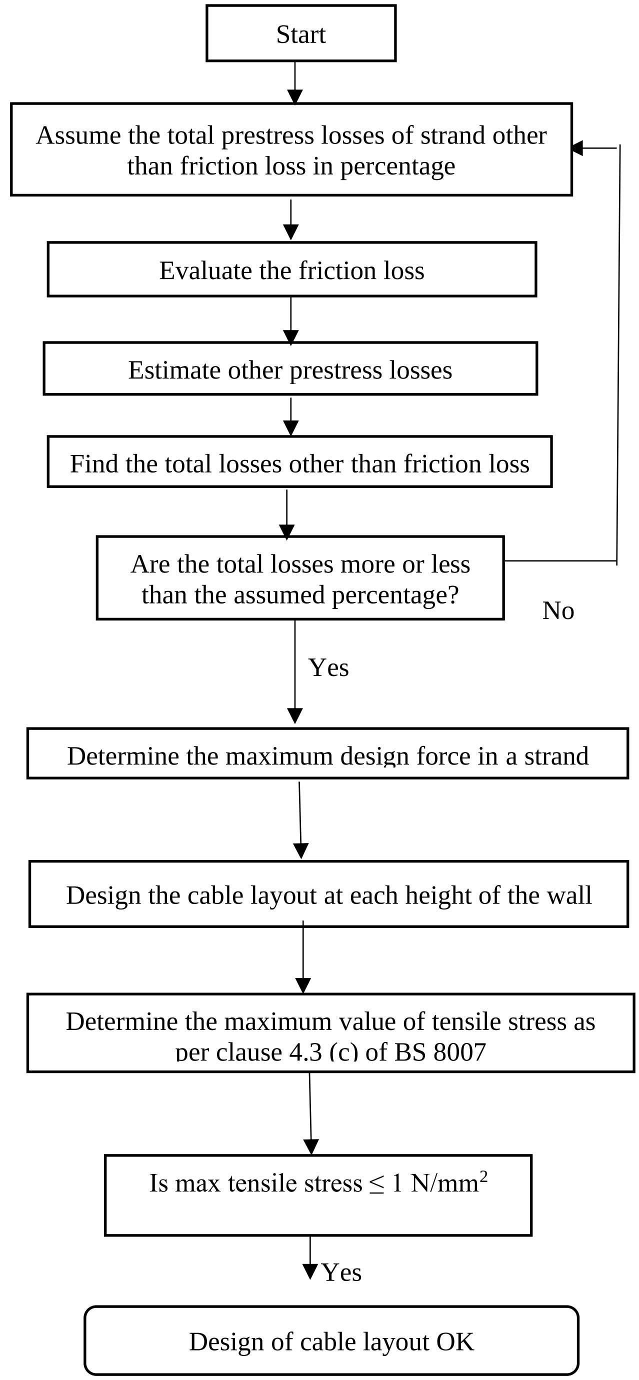

Fig. 8. Procedure of post tensioned prestressed concrete design of circular tank

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D. Cost comparison of RC and PC water tanks

The drawings of tanks were produced after the completion of RC and PC design. Then bill of quantities of each tank for each design approach was prepared with the assistance of drawings and rates of water retaining structures from NWSDB and other resources. Eventually, the costs of all tanks in each design category were revealed. All obtained results of cost were compiled in Table 2. Fig.9 compares the costs of RC and PC tanks depending on their capacity.

TABLE 2: SCHEDULE FOR RC & PC WATER TANKS ESTIMATED DETAILS

Tank capacity (m^3)	Cost of PC tank (Mn)	Cost of RC tank (Mn)	% of saving
1500	21.05	19.01	-10.68
2500	35.80	34.33	-4.29
3500	41.28	41.88	1.45
4500	52.43	60.91	13.93
5500	61.72	70.33	12.23
6500	71.38	82.60	13.59

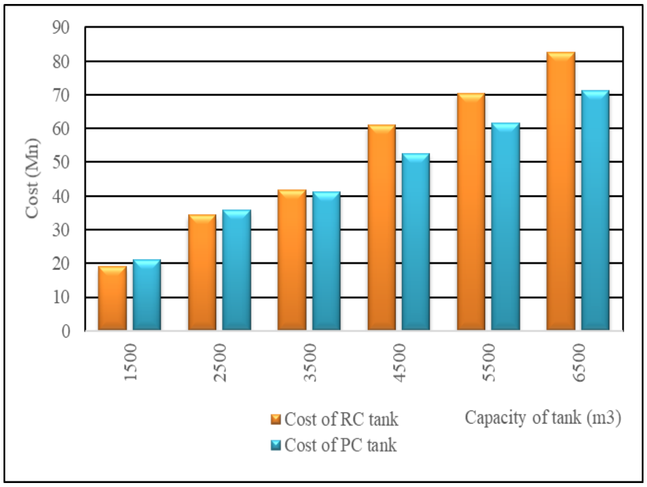

Fig. 9. Cost comparison of PC and RC water tanks depending on the capacity

As shown in Fig. 9, the cost of a PC tank is slightly higher than the cost of an RC tank from 1500 - 2500 m3 capacities. Overall, the cost difference between the RC and PC tanks is less from 1500 - 3500 m3 capacities. The cost of a PC tank is considerably reduced compared to that of a RC tank beyond 4500 m3 capacity. As per Fig. 10, the cost of reinforcement in PC tanks is generally higher than the costs of reinforcement in RC tanks for smaller capacities (1500 - 3500 m3).

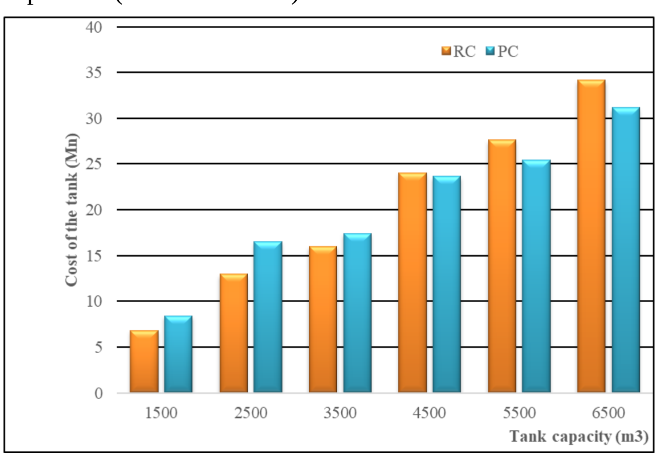

Fig. 10. Reinforcement cost comparison of PC and RC water tanks depending on the capacity

The post-tensioning work reduces the amount of reinforcement of tank walls in PC design, especially for higher capacity tanks (beyond the 4500 m3).

The chart shown in Fig. 11 compares the cost saving of PC water tanks compared to RC for different capacities. As the tank capacity increases, the cost of tank increases. For tank capacities beyond 4500 m3, PC water tanks show a cost saving about 12-14% compared to RC tanks. This is because RC water tanks with higher capacities requires higher wall thickness consuming higher amount of reinforcement and concrete quantity.

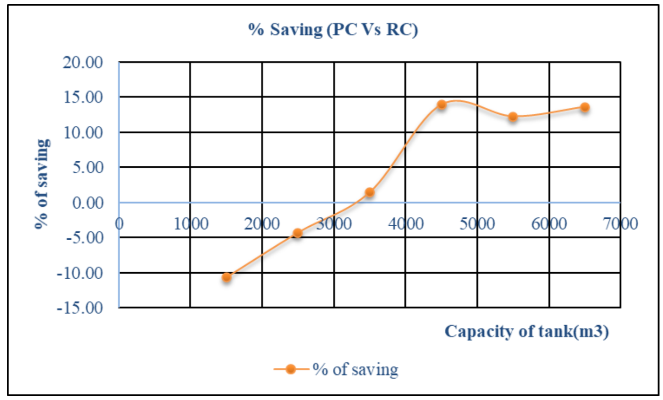

Fig. 11. Variation of % of saving for given capacity

The cost of RC and PC water tanks are further compared in Fig. 12. It is clear that, up to 4000 m3 capacity both PC and RC show similar cost, while beyond about 4000-4500 m3 capacity, PC water tanks seem to be economical than the RC tanks.

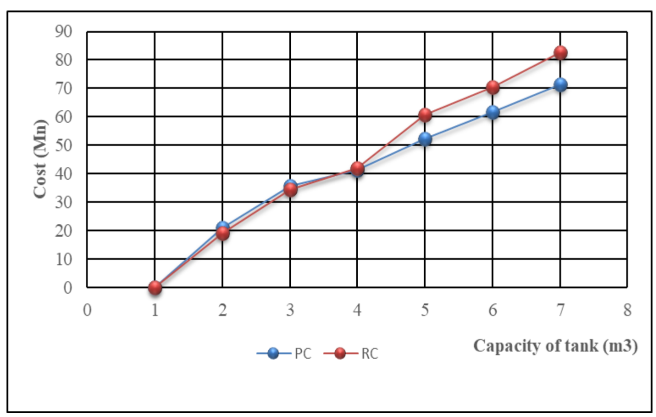

Fig. 12. Variation of cost of tank with capacity and design methodology

V. CONCLUTION

This paper has investigated the economic feasibility of PC water tanks compared to those of RC for different tank capacities. Results from the questionnaire survey revealed that PC tanks are not that popular in Sri Lanka due to lack of construction technology and lack of design knowledge. Results from the finite element (FE) analysis indicated that RC design approach is generally a better choice for smaller tanks having a capacity up to 4500 m3. PC design approach is economical for bigger tanks having a capacity beyond 4500 m3. Post tensioning significantly reduces the amount of reinforcement required for the tank walls in bigger tanks. For higher capacities, Prestressing is the superior choice resulting in a cost saving of about 12-14% compared to RC tanks.

REFERENCES

[1] P. A. Calderón, J. M. Adam, and I. Payá-zaforteza, "Failure analysis and remedial measures applied to a RC water tank," *Eng. Fail. Anal.*, vol. 16, no. 5, pp. 1674–1685, 2009, doi: 10.1016/j.engfailanal.2008.12.004.

[2] A. Younis, U. Ebead, P. Suraneni, and A. Nanni, "Cost effectiveness of reinforcement alternatives for a concrete water chlorination tank," *J. Build. Eng.*, vol. 27, no. September 2019, p. 100992, 2020, doi: 10.1016/j.jobe.2019.100992.

[3] A. Gunatilaka, "Water security and related issues in Sri Lanka: The need for integrated water resource management (IWRM)," *J. Natl. Sci. Found. Sri Lanka*, vol. 36, no. Special Issue, pp. 3–15, 2008, doi: 10.4038/jnsfsr.v36i0.8045.

[4] M. Bhandari and K. D. Singh, "Economic Design of Water Tank of Different Shapes With Reference To IS : 3370 2009," vol. 4, 2014.

[5] P. of the P. Technology, "Pioneer of the PC Technology," 1957.

[6] M. S. R. Metkar, "Economics of R . C . C . Water tank Resting over Firm Ground vis- a-vis Pre-stressed Concrete Water Tank Resting over Firm Ground," vol. 1, no. 1, pp. 1–17, 2013.

[7] "Post-Tensioning Tendon Installation and Grouting Manual," no. May, 2013.

[8] I. B. and R. Westbrook, *Design tables for water retaining structures*. 1991.

[9] M. J. N. Priestley, "Analysis and Design of Circular Prestressed Concrete Storage Tanks.," *J. - Prestress. Concr. Inst.*, vol. 30, no. 4, pp. 64–85, 1985, doi: 10.15554/pcij.07011985.64.85.