CIRCULAR AND SQUARE TANKS – A STUDY OF EFFICIENCY

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SUMMARY

This paper is an investigation into the efficiencies of square (or rectangular) and circular prestressed concrete tanks. This is a look into which geometry is more suitable to particular design requirements. I have also compared two tanks which I have personally designed. I have found that, in general, circular tanks appear to be more materials efficient than square (or rectangular) tanks. This will not always be the case as it is dependent on the combination of design requirements for a particular tank.

INTRODUCTION

This paper will investigate prestressed (and to a lesser extent reinforced) concrete square and round tanks and the benefits and downfalls of these two types of common structural systems. Efficiencies can be gained by making correct design decisions based on the particular situation. The focus will be on the efficiencies which can be gained, primarily in the construction process, but also during design.

Prestressed concrete tanks are commonly constructed as either square (rectangular) or round. This simple change in geometry completely alters the way the tank will work structurally. For square tanks, the wall panels span vertically between foundation and some form of structure at the top of the tank, either a roof or a ring beam. For circular tanks, the structure utilises hoop stress around the tank meaning that no roof structure or ring beam is needed and stresses to the foundations are reduced.

Recently, I have been a designer for both a square and a round tank. For a simple comparison I will investigate which was more efficient for various aspects of construction. In this paper I will refer to them as Tank 1 and Tank 2. The first tank is square with prestressed wall panels spanning vertically and holds 1.2 million litres. It has a hollowcore roof with concrete topping slab which is structurally necessary for carrying hydrostatic and seismic loads. This tank has a dividing wall through the centre which adds an extra aspect to the construction and to how it works structurally.

The second tank is round, prestressed vertically and post tensioned horizontally and holds six million litres. There is a flat panel with topping slab roof which does not contribute to the tanks ability to carry any form of loading.
EFFICIENCY OF AVAILABLE LAND

Available land for constructing a tank is typically square or rectangular therefore square tanks will be the more efficient geometry for utilising the available land. Constructing a circular tank instead of a square tank in the same available area only utilises 78% of the area. Therefore, for a circular tank to have the same volume as a square tank it would need to be 27% taller. If the available building site is rectangular, the amount of utilised area when building circular tanks is even further reduced. This is shown in the below Figure 1.

![Figure 1 – The Ability of a Circular Tank to use Available Land](image)

Specific Tank Comparison

Tank 1 is built on a small site with not much usable area to locate the tank. This would have been a contributing factor in choosing a square footprint to optimise the land area.

Tank 2 has more available land to use. The available land therefore did not have much bearing on which shape was adopted.

EFFICIENCY OF MATERIALS

Materials efficiency is essential in achieving an efficient and economical design. Due to cranage on site, transport and placement of units it is often most beneficial to the project as a whole to minimise the overall quantity of concrete needed especially in the wall panels. The best way of achieving this is to have as slim as possible wall panels.

In the vertically spanning arrangement of a square tank, the wall panels are working in bending. For reinforced or prestressed concrete, the bending capacity of a panel is dependent on the thickness of the panel and the amount of reinforcing or prestressing in the panel. For a reinforced concrete panel, a thicker panel is required when compared to a prestressed panel.

With a circular tank, forces are resisted by hoop stress and the capacity is therefore dependent on the amount of prestress and not the thickness of the wall. The ultimate result of this is that square tanks generally need thicker panels than circular tanks.
For both types of prestressed tanks, the normal reinforcing required is just a nominal amount (except for the roof of a square tank as mentioned below) so I will not look into this with any real detail.

Specific Comparison

Tank 1 is 16 by 16 by six metres tall. Although being reasonably short, the fact that the panels are simply supported from the ground to the roof means that the panel thickness needed to be 300mm. This led to the following amounts of materials being used:

- Floor slab: minimum 150mm thick over a surface area of 250 square metres gives 37.5 cubic metres of reinforced concrete.
- Perimeter Walls: 64m of 300mm thick wall gives 19.2 cubic metres of concrete (ignoring the dividing wall)
- Roof: 200mm hollowcore units gives a gross volume of 28 cubic metres of concrete with a 110mm topping giving another 28 cubic metres of concrete (there was a high percentage of reinforcing needed in this)
- Prestressing strand (in perimeter walls only): 440 number 12.7mm diameter strands, 6m long giving a total of 2,640 linear meters.

Tank 2 is 30m in diameter and nine metres tall. The panels are prestressed vertically and then also post tensioned horizontally. The use of the horizontal hoop stress is an effective and efficient means of carrying loads. This meant that the wall panels adopted are only 200mm thick. The following amounts of materials were used for Tank 2's construction:

- Floor slab: 150mm thick over a surface area of 700 square metres gives 105 cubic metres of reinforced concrete
- Walls: 94m of 200mm thick wall gives 18.8 cubic metres of concrete
- Roof: 110mm thick prestressed panel and 90mm of topping gives 140 cubic metres of concrete
- Prestressing strand: 656 verticals at 9m long and 108 horizontals at 94m long giving a total of 16,056 linear metres.

The above data is summarised in the below Table 1. While the absolute values are of interest, it is also important to see how much material is need per volume of water. The table has therefore been normalised per 1 million litres of capacity.

<table>
<thead>
<tr>
<th></th>
<th>Tank 1</th>
<th>Tank 2</th>
<th>Tank 1 normalised</th>
<th>Tank 2 normalised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors slab (m³)</td>
<td>37.5</td>
<td>105</td>
<td>31.25</td>
<td>17.5</td>
</tr>
<tr>
<td>Perimeter walls (m³)</td>
<td>19.2</td>
<td>18.8</td>
<td>16</td>
<td>3.1</td>
</tr>
<tr>
<td>Roof (m³)</td>
<td>56</td>
<td>140</td>
<td>46.7</td>
<td>23.3</td>
</tr>
<tr>
<td>Wall strand (m)</td>
<td>2,640</td>
<td>16,056</td>
<td>2,200</td>
<td>2,676</td>
</tr>
</tbody>
</table>

From the Table 1 above, it can been seen that the amount of concrete, especially after the values have been normalised, for Tank 2 (the round tank) is far less than Tank 1. There is, however, more strand used per million litres of capacity in Tank 2 when compared to Tank 1.
SPEED OF CONSTRUCTION

A quicker construction period of a tank invariably leads to reductions in costs such as overheads and plant hire, a reduction in disruption on site and the ability for the Client to use their asset earlier.

The factor which has the biggest influence on speed of construction is the amount of work to be done on site. The major jobs on site include; earthworks, foundation, floorslab, panel placing, panel stitching, sealing of the tank and construction of the roof. Another factor is the amount of precasting to be produced but this can generally be started before the Contractor gains possession of site and can then stay ahead of programme on site so is therefore generally a non-critical item in terms of project programming.

Areas where efficiencies in speed of construction can be gained with a square tank over a circular tank are in the foundations and the panel stitching. The foundations can be sped up by adopting a precast foundation option as this is fairly straightforward with square tanks. In terms of panel stitching, there is no need for post tensioning so an extra step is eliminated when compared to a round tank.

Areas where efficiencies can be gained with a circular tank over a square tank are in the panel placing, as there are generally less panels compared to a square equivalent, sealing as there are less joints and in the roof construction as it does not need to contribute structurally to the tanks water retaining capability so is generally a more streamlined roof system.

Specific Comparison

Tank 1 used a precast foundation system. This is beneficial in terms of speed of construction and cuts out a lot of the required form work on site which is labour intensive. 30 wall panels were used (six of which were needed for the dividing wall) weighing typically 10.4 tonnes which needed stitching either side. The roof was placed needing a highly reinforced topping as it acted as a structural diaphragm. The high level of reinforcing in the topping is labour intensive and being on a roof top makes it slow going also.

Tank 2 being round meant that precast foundations are not unachievable but insitu foundations were ultimately adopted. 32 wall panels were needed, with the typical panel weighing 12.4 tonnes. The panels needed to be stitched together and then post tensioned after being placed. Although the topping was lightly reinforced, it did need a column and beam structural system to span the 30 metre diameter of the tank.

EFFICIENCIES OF GEOMETRY

The main elements of a tank are the floor, walls and roof. It makes sense to minimise the combination of these whilst still keeping the same volume. For a square tank, this would be a cube and for a circular tank it would be a shape where the diameter is similar to the height. But, the greater expense is in the wall panels so it makes sense to decrease the height of the tank and increase the plan area of the tank until the optimum value is found given weightings on the floor, walls and roof.

Specific Comparison

Tank 1 is 16 by 16 by six metres tall. This is an expected ratio of height to plan area which has more floor and roof area than a cube but has not gone too far so that the floor and roof areas are excess and unmanageable.
Tank 2 is 30m in diameter and nine metres tall. This too is an expected ratio and suitable for this tank.

**TANK DESIGN**

The design is where the implementation of efficiencies needs to occur. Each type of tank comes with its own range of design issues and complexities. Reduced complexity of design is obviously beneficial for the designer and can therefore lead to a reduced design cost. A simple design also has the benefits of simple detailing and the possibility of repetition in construction which is often a good way to reduce build costs.

As mentioned previously, square and circular tanks have two very different structural systems. Square tanks have wall panels spanning vertically while round tanks utilise horizontal hoop stress. This means that each type of tank has a different means of dealing with the different loads which it must carry. There are three main design loads that a tank must carry. These loads are hydrostatic, earthquake and temperature which are each discussed in the following sections.

While all of the main design loadings need to be considered, they obviously vary from tank to tank and so the weighting given to each design loading needs to be carefully considered when choosing which shape and height of the tank will be most beneficial for the situation.

**Hydrostatic**

Hydrostatic forces are the loading that the tank has to deal with on a day to day basis. It is generally easy to predict and calculate these forces. Given a liquid provides an equal stress in all directions, the forces due to hydrostatic are the same on each wall and always perpendicular to the wall and there is no net lateral force produced on the tank as a whole.

For square tanks, the force on the walls is only dependent on the height of the retained water. Therefore, a big footprint area compared to the height of the tank is more efficient for a square tank. If the wall length to height ratio is high, for example two or more (which is more than often the case), the walls effectively span one-way from the roof to the foundation and do not pass any force along the walls to the perpendicular walls. For walls with lesser length to width ratios some two-way action of the wall panels can be achieved but if a tank has a low length to height ratio it must be tall compared to its surface area in order to have a decent volume and is therefore a less efficient in terms of design loading. For circular tanks, the hydrostatic demands are linearly proportional to both height and diameter. Therefore, given that volume is linearly proportional to height but exponentially proportional to diameter, it make sense to have a high diameter to height ratio in some instances.

For both types of tank when considering hydrostatic design, it is theoretically beneficial to maximise the surface areas and minimise the heights of the tank to get the most efficient design.

For square tanks, the hydrostatic forces are firstly applied to the walls. The walls pass a proportion to the foundation and a proportion to the roof as a tensile force (if there is two-way spanning being achieved a proportion will also go to the walls perpendicular to the wall in question). Given the forces on all the walls are equal and in opposite directions, the tensile force in the roof is resisted by the tensile force produced due to the wall directly opposite. With a circular tank, the only stresses developed under hydrostatic loading is the hoop stress felt by the walls with generally no horizontal force being transferred to the roof or floor of the tank.
Seismic Design

There are many factors which influence the seismic force that a tank will be designed to resist. These include location effects such as seismicity of the area and soil conditions and also factors for importance of the structure. For a tank which provides a town water supply for instance, there will generally be a high importance on the tank so it is still functional or easily fixed after a seismic event. This will increase the seismic force to be designed for when compared to a structure of low importance.

Seismic load in a tank comes in two forms, impulsive and convective. Impulsive represents the load produced by the contents of the tank being accelerated by the earthquake and convective represents the load produced by the oscillating contents in the tank. The weight of the structure itself is also accelerated at the impulsive accelerations.

The New Zealand Standard for the Design of Concrete Structures for the Storage of Liquid, NZS 3106:2009 has various formulas and charts for the calculation of seismic loads. Many of the design coefficients in the code vary based on the ratio of the radius to height (or the ratio of half the length to height when looking and square tanks). As this ratio of the radius to height increases, the percentage of water that acts impulsively decreases but the percentage of water that acts convectively increases. Conversely, as this ratio increases, the design acceleration generally increases for impulsive but decreases for convective. It therefore means that the lesser weight impulsively multiplied by a greater acceleration and vice versa for convective somewhat evens out when comparing a range of tanks. The weight of the structure also has an influence, but, as it is only dependent on the impulsive acceleration, the seismic force from the structure will therefore be reduced if the ratio is decreased.

As a very broad generalisation however, the greater the radius (or length) to height ratio, the lesser the seismic loads (for the same volume), especially if the structure is light compared to the volume of water it is containing.

For a square tank, seismic loads are applied to the walls as face loads. The loads are then transferred to the foundation below and up to the roof in a similar way to how the hydrostatic forces are resisted. The difference from hydrostatic comes in the fact that there is no longer an equal tensile force from the wall opposite the one in question. The roof therefore needs to act as a diaphragm and have enough shear and bending capacity to get the applied forces out to the walls perpendicular to the applied load. These walls then carry the force down to the foundation.

For a round tank, the hoop stress carries the force around the tank and distributes the base shear as a maximum perpendicular to the direction of loading decreasing to nothing at 90 degrees to this. The loads are transferred to the ground in the same way as a shear wall works in a building. The below Figure 2 shows the distribution of forces at foundation level.
Additional considerations due to seismic are the vertical accelerations and the wave generated by the convective sloshing of the liquid. Vertical acceleration produces loads of a form identical to the hydrostatic loads but of different magnitude. For a vertical acceleration of 0.25g, the hydrostatic force essentially increases by 25%. A convective wave is produced in the tank due to the sloshing of the liquid. The height of this wave is dependent on the convective seismic mode and the radius (or half the length of a square tank). This wave height can govern the freeboard necessary or alternatively, the roof structure can be designed to resist the upward force of the wave pressure which is dependent on the differences in unrestrained wave and freeboard as shown in the below Figure 3.

**Temperature**

Environmental temperature differentials produces an increase in stress in the walls and roof of the structure. The requirements for the range of temperature the tank needs to be designed to in New Zealand are the same all over the country. Temperature induced stresses can lead to cracking in the tank. Code limits specify the level of water tightness that the tank needs to achieve which therefore dictates the size of the cracks which are acceptable. The design can then be detailed according to the level of water tightness it needs to achieve.
The severity of the temperature loading is dependent on the geometry of the tanks. In square tanks, large concentrations of stress develop in the corners which has to be accounted for in design. With a round tank, the uniform nature means that there are no concentrations of stresses. The differences in the stress is only loosely affected by the size of the tank.

**Overall Design Considerations**

Combining all of the above aspects gives an optimum tank design. Generally, for low seismic areas, maximising the surface area and minimising the height is a good option. This is most beneficial for a square tank as the hydrostatic and temperature demands remain low when the height of the tank is low. But, to do this, a large amount of available land is needed which is not always achievable and the floor and roof area per volume of liquid retained increases with a shallower tank as previously mentioned.

If seismic loading for a specific tank is high, a square tank will not work well if it is too big in plan as the force which is needed to be transferred through the roof becomes increasingly unmanageable.

Other things to consider are that in a round tank, each panel has the same or similar design forces whereas with square tanks, depending on the geometry, the panels can all have very different design loads. This means a trade-off is needed; keep similar detailing throughout the panels for ease of construction but not having all the panels working as efficiently as possible or detail several options for different points in the tank where all panels are efficiently designed.

**Specific Comparison**

Tank 1 has a width to height ratio of approximately three. This means that the hydrostatic pressures on the precast walls are only really carried by vertical spanning between foundation and roof. In other words, the walls under hydrostatic loading feel as much load as if the tank was infinitely bigger in plan. The panels also feel sharp peaks in stresses due to temperature loading. The seismic loads are carried by face loading in the wall panels which loads the roof. The roof therefore needs to be designed to carry these seismic forces from the loaded walls to the walls parallel to the direction of the seismic load.

Tank 1, having the dividing wall, meant that the design was slightly more complex than if it were not divided but the wall did provide some efficiencies in design. The dividing wall meant that the walls in one direction were only eight metres long and could effectively act as a two-way spanning panel. It also meant that the full length wall had half as much water to retain seismically (hydrostatic is not reduced due to the dividing wall). It did also give a ledge for the roof panels to land on so that they only needed to span eight metres rather than 16 m.

Tank 1 had a number of different panels due to the panels each having varying temperature and seismic actions and to an extent varying hydrostatic loads. This meant that there were a lot of different panels to design and construct.

Tank 2 utilises hoop stress to carry the hydrostatic loads. The temperature loads are uniformly dispersed around the tank. The seismic loads are easily accounted for due to hoop stress and wall panel shear capacity. The roof did not need to contribute to the tank's structural performance which led to a lightly reinforced and simply detailed roof and supporting columns. The roof was needed to restrain the convective wave and so detailing was required to keep the roof from being pushed off during a seismic event.
CONCLUSION

For the tanks which I have designed and compared in this paper, the circular tank was found to be more efficient and economical. The beneficial points were:

- Slimmer panels and less concrete required
- Low number of panels (given the size of the tank) which leads to reduced transport, placing and stitching costs
- All panels were loaded the same and therefore they were consistently detailed while still being efficient
- The roof structure was simpler and more efficient (especially considering the size of the tank)

Judging from my experience, the more efficient tanks are round in plan with post tensioned hoop reinforcing. Which geometry, square or round, is the most efficient for a particular tank serving a particular purpose is dependent on a number of factors. The factors which favour either geometry are listed below:

- Situations where square tanks may be more beneficial:
  - Where available land is limited (or rectangular in shape)
  - Where concrete and transport costs may be low compared to prestressing costs
  - If seismic demands are low (Auckland for example) but total volume to be retained is medium to high (greater than 10 million litres)

- Situations where round tanks may be more beneficial:
  - Available land is not an issue
  - Isolation or high transport costs mean amount of concrete needs to be minimised
  - High seismic areas

REFERENCES

New Zealand Design Standard, Design of Concrete Structures for the Storage of Liquids, NZS3106:2009