Reinforced Concrete Cylindrical Storage Structures for Aqueous Materials in Cold Climates

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Synopsis: A study of concrete water tanks in the Province of Ontario indicated an unusually high rate of deterioration. The different types of tanks in existence are described. Observed defects and the possible related mechanisms are discussed. Particular attention is directed to freeze-thaw cycles and internal ice formations and methods for estimation of these effects are proposed. Criteria and recommendations for the design of reinforced concrete storage structures in both freezing and non-freezing environments are discussed.

Keywords: deterioration; freeze-thaw durability; ice formation; load factors; low temperature; reinforced concrete; structural design; water tanks

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INTRODUCTION

A study (1, 2), commenced in 1981, of 53 concrete water tanks in the Province of Ontario indicated an unexpectedly high rate of deterioration. It was expected that the life of a water tank should be in excess of 50 years, but most of the tanks studied were less than 9 years old with an average age of about 6 years. Two water tanks had failed prior to initiation of the study.

As shown in Fig. 1, there are essentially three different categories of water tanks: standpipes, elevated tanks and ground tanks. Standpipes are cylindrical structures up to 46 m (150 ft.) high and 7 to 9 m (25 to 30 ft.) in diameter. Large storage capacity and high internal water pressure in the lower portion of standpipes are distinct features of this category of tank. Elevated tanks have a smaller storage capacity but are capable of providing high operating head with relatively low internal head, approximately 10 m (30 ft.). Ground tanks have a low operating head, about 10 m (30 ft.), but have a large capacity due to their diameter, up to 30 m (100 ft.). These tanks are constructed at the ground level and can be classified as low head tanks. Within each of above three categories, as listed in Table 1, there are three main structural types, namely, non-prestressed reinforced concrete, post-tensioned wire wound concrete and post-tensioned concrete with tendons, either bonded or unbonded.

Performance ratings of the 53 tanks were determined by means of surveys using measurement standards (1) for rating the condition of all major components. These surveys indicated that standpipes had the worst performance and ground tanks the best.

This paper describes ten of the main defects found in the tanks. These defects may be attributed primarily to inadequate design criteria and faults in construction. Possible mechanisms causing the various defects are described in general with particular attention directed to the effects of freeze-thaw cycles and internal ice formations. Design recommendations for cylindrical storage containers located in either a non-freezing or a freezing environment are discussed.

DEFECTS IN TANKS

The ten main defects revealed in the surveys of the tanks are listed in Table 2. It was found that each tank had its own deterioration peculiarities. However, several types of defects can be associated with individual tank types.

Wall Delamination

Vertical wall delamination, or splitting of the concrete in the plane of the wall, has been observed in all types of tanks. The mechanism and causes are similar, but may vary according to the type of construction.

Large areas of vertical delaminations have been observed in non-prestressed reinforced concrete standpipes. The splitting cracks are located at the centre of the tensile hoop reinforcement, thereby separating the wall at these locations into two or three individual cylindrical surfaces. The walls of these delaminated standpipes are radially cracked on vertical lines at about 250mm (10 in.) centres and generally leak when temperatures are above freezing. Delaminations have been observed to grow in freezing weather. Mechanisms by which these delaminations may be formed are discussed later.

Delaminations centred on ungrouted post-tensioning tendon ducts have also been observed. It is assumed that water under pressure gradually penetrates the wall and fills the ungrouted void. On freezing, the confined ice expansion within the void causes both vertical (delamination) and horizontal cracking through the wall. This cracking may cause explosion of a tank when full, or implosion as a tank is being emptied.

Vertical delaminations have been found in gunited (shotcreted) walls. It is assumed that these cracks are at weak planes where individually placed layers of gunite have not bonded together because of hardening of the first layer before the new fresh layer is sprayed on. Freezing of water which has penetrated into these cold joints can cause cracking.

Vertical Cracks in Wall

Vertical cracks have been observed over the entire height of the walls in non-prestressed reinforced concrete standpipes under normal water loads. The width of the cracks and rate of leakage from the cracks depend on a number of factors including, but not limited to, concrete strength at time of filling, tensile stress in the hoop reinforcement and type or lack of waterproofing. While cracking in the lower regions of the wall may be due to water pressure, the vertical cracks in the top regions are thought to have been caused by the expansion of internal ice formations. The effects of internal ice formations are discussed later.

Vertical cracks have occurred at the bottom of a ground tank due to ineffective prestressing caused by restraint against inward movement at the base during construction.

Wall/Floor Joint Deterioration

Both sliding and fixed wall-floor joints have exhibited leakage and local deterioration near waterstops. Leakage is caused by poor installation of the waterstop, holes in the waterstop and permeable concrete around the waterstop. Severe deterioration of concrete on the inside of waterstops has been observed. This is caused by freeze-thaw damage of the concrete due to the waterstop acting as a dam, allowing complete saturation of the concrete.

Vertical Voids in Shotcrete

Voids outside the vertical reinforcement and under the prestressing wires has been observed in gunite protected tanks. This is caused by poor workmanship allowing the reinforcing bars to act as shields which block the mortar spray and thereby cause the voids.

Jack Rod Spalls

Some tanks had been constructed using a slip form method. Hollow pipe rods, known as jack-rods, each approximately 3 m (10 ft.) in length are used to raise the slip form. As construction proceeds, additional lengths of rod are added using threaded solid coupling rods. This results in hollow tubes, interrupted at each joint by a solid rod, spaced at approximately 3 m (10 ft.) centres around the wall and extending the full height of the tank.

Many large conical spalls have occurred at the joints in the hollow jack rods. In some tanks, little attempt was made to seal these jack rods at the top of the tank and water was able to enter the uppermost jack rod section. This water leaks out at the threaded couplings in each jack rod and saturates the surrounding concrete. When water in the jack rod freezes, the ice expansion combined with freeze-thaw action, causes high concentrated forces in the middle of the wall, resulting in explosive conical spalling at the location of coupling with a cone height equal to half the wall thickness. Internal water under pressure can then enter the jack rod at the location of a spall causing even more rapid deterioration at all couplings over the length of a jack rod.

Shotcrete Cover Coat Delamination

On some tanks where a cover coat of shotcrete has been applied to the prestressing wires, delamination of the cover coat has occurred where the applied mortar layer is too thin approximately 10 mm (0.5 in.). Cover coat delamination has also been observed in local areas where the spacing of the prestressing wires is too small. Close wire spacing does not allow adequate bonding among the cover coat layers since the smooth wires act as a debonding medium. Thick cover coats, greater than 25mm (1 in.), have not exhibited delaminations.

Waterproof Coating Failure

Most failures of the internal waterproof coating have been caused by lack of adequate bond of the coating to the concrete wall. This may be attributed to a number of factors such as the use of poor materials, poor workmanship, poor surface preparation, and application of the coating on damp concrete surfaces, or under environmental conditions of high humidity and low or high temperatures. Many coating failures may be attributed to freeze-thaw action at the interior surface.

Shotcrete Cover Coat Cracking

Cracking of the shotcrete cover coat can be attributed to shrinkage as a result of rapid drying and/or insufficient or lack of curing of the young concrete mortar.

Cold Joints and Horizontal Cracks

Leaking cold construction joints in jump-formed concrete tanks are common, and are mainly caused by lack of waterstops and/or poor workmanship and preparation at the joints. Cracks at horizontal joints are common and are caused by shrinkage due to lack of curing or by temperature differential through the wall. Horizontal cracks resulting from the lack of vertical reinforcement in the wall have been observed at locations of high moment resulting from temperature differential, particularly at a region where a stiff floor slab joins the wall in an elevated tank (21).

Corrosion of Prestressing Steel

Loss of the protective gunite cover coat from the prestressing wires in wire wound tanks has resulted in general corrosion and wire failure causing loss of circumferential prestress. This prestress loss results in vertical cracking of the tank wall. Poorly filled external post-tensioning anchorage recesses have permitted water to enter horizontal unbonded post-tensioning tendons resulting in stress-corrosion failure of the strands. Lack of grout in ducts has allowed water to enter causing general corrosion of the prestressing steel.

It can be seen that, in general the observed defects in the tanks surveyed are due to inadequate design criteria and/or faults in construction. The influence of a freezing environment on the observed deterioration is apparent. The effects of freeze-thaw cycles and internal ice formations on the behaviour of a tank are discussed below. Methods of repairing defects in water tanks are outlined in Ref. (3).

STUDIES OF MECHANISMS CAUSING DEFECTS

A number of studies were undertaken in an attempt to explain the causes of some of the observed defects. Two of these studies, namely temperature monitoring and the effects of freeze-thaw cycles, are discussed in Ref. (3), while a third, the effects of internal ice pressure, is reported in Ref. (4). These three studies are described briefly below.

Temperature Monitoring

A temperature monitoring system was installed in three tanks, two with insulation and one without, to provide information relating to the climatic influence on the tanks.

Figure 2 shows data obtained from an uninsulated tank during the winter period. Figure 2(a) indicates that temperatures in the north exposure are almost continuously below freezing throughout January, while from Fig. 2(b), it can be seen that freeze-thaw cycling occurs almost daily in the south exposure during the same period.

Further, temperature records of the tank water, obtained during sub-zero ambient conditions, indicate that the tank water provides very little buffering effect and suggests that little water circulation takes place inside the tank. Water quickly freezes close to the wall of the tank forming an ice ring around the inside of the wall. Temperature variation in the water indicated that an ice cap forms at the top of the tank. Visual observations confirmed the presence of the ice cap throughout the winter period.

Figure 3 shows a graphical record of temperature variation during the winter period for an insulated tank. The insulation consisted of rigid styrofoam sheets covered by corrugated metal cladding. An air gap was left between the styrofoam and the wall of the tank. The significant moderating influence of the insulation is obvious. The temperature fluctuation in the air gap is about one third that of the external ambient temperature. The temperature of the water in the tank is largely independent and isolated from the ambient conditions.

Temperature data obtained from the uninsulated tank indicate that freeze-thaw cycles occur in the wall, particularly in the south exposure. Also it was seen that ice formations, in the form of an ice cylinder on the inside of the wall or an ice cap at the top surface, may exist. The effects of freeze-thaw cycles and the presence of these ice formations and their relations to possible deterioration of the tank wall are now discussed.

Effects of Freeze-Thaw Cycles

The surveys revealed that the internal waterproofing system had broken down, allowing water under pressure to penetrate the walls, resulting in saturation of the concrete. Saturated concrete expands when it freezes and a residual expansion or dilation is produced upon thawing (5).

Figure 4 shows a situation where the outside part of a wall of a concrete tank dilates due to freezing and is in compression, while the inside part is unaffected by frost and is in tension. Restraint to this tendency of differential movement induces radial tensile stresses which vary throughout the thickness of the wall as shown in Fig. 5. The maximum tensile radial stress occurs at the interface between the dilating zone and the inner zone of the wall and attains a peak value when the dilating zone occupies one half the wall thickness.

The build-up of radial tensile stress predicted by a mathematical model (3) for a typical tank wall is shown in Fig. 6. The model assumed that 60 cycles of freezing and thawing occur during a two month period each year with frost penetration to the middle of the tank wall. It can be seen from Fig. 6 that tensile stress increases over this two month period and reduces over the next ten months due to relaxation, and that the permeability of the concrete is one of the most important parameters. Higher stresses are developed in concrete with higher permeability.

Radial tensile stresses in the order of 2 MPa (290 psi) can develop in high pressure standpipes over a five year period when the concrete permeability is 8×10^{-12} m/s (26×10^{-12} ft/s) and the dilatancy strain is 1×10^{-4}. The presence of reinforcing steel in the wall induces stress concentrations which can magnify the radial tensile stress in the vicinity of the reinforcement by a factor of 2 to 4. Consequently, tensile stresses large enough to split the concrete in the plane of the reinforcement causing delamination in the wall can be induced.

The radial tensile stresses in the wall will be counteracted by the presence of post-tensioning to a certain degree. A post-tensioned tank therefore would require more freeze-thaw cycles to cause delamination. This supports field observations that reinforced concrete standpipes are more susceptible to delamination than are post-tensioned tanks.

Another mechanism which could result in the generation of considerable hydraulic pressure in the wall of a tank has been termed the hydraulic pressure sandwich. Figure 7 shows sketches representing possible thermal conditions which may result in an unfrozen centre zone in the tank wall. Figure 7(a) indicates a condition where the ambient temperature has been below zero for a considerable period resulting in the formation of an interior ice ring in the tank and frozen concrete throughout the thickness of the wall, followed by a warm period which partially thaws the outer part of the wall. As shown in Fig. 7 (b), the cycle is completed by the ambient temperature returning to below freezing resulting in a thawed central region in the wall, an inward moving freezing front, and an impermeable frozen zone in the interior wall section. As described by Adkins (6), this can result in trapping a lens of unfrozen water which expands upon freezing, causing tensile forces in the tank wall. The location of the unfrozen water layer will determine the plane of failure and resulting delamination, which will be manifested as external or internal scaling.

Effects of Internal Ice Formations

Ice formations consisting of a floating ice cap and/or an ice tube on the walls of water tanks have been observed. Pressure will be exerted on the wall of a tank as a result of rapid warming and related expansion of such ice formations. Hoop and flexural stresses will be developed in the walls as a result, with the ice cap representing a more severe loading case than the ice tube. A method of computing the stresses induced by an ice cap has been developed by Kong (7) and Kong and Campbell (8). Computation of hoop stress is summarised below.

Ice is a thermoviscoelastic material in that its behavior under stress is a function of time and temperature. Bergdahl (9) has proposed the following four parameter model, to describe the behavior of ice under pressure:

$$\dot{\epsilon} = \dot{\sigma}/E + BD\sigma^n \quad [1]$$

where $\dot{\epsilon}$ is the strain rate, $\dot{\sigma}$ is the stress rate, E is the modulus of elasticity, D is the self-diffusion coefficient and B and n are coefficients of viscous deformation. The validity of this model has been established by comparing its predictions with test data (7).

Figure 8(a) shows an ice cap contained within a long cylinder. If creep of the ice is neglected (creep effect is introduced later), and if it is assumed that a linear pressure distribution develops when the ice cap is subjected to an increase in temperature, which varies linearly over the thickness (Fig. 8(b)), the problem reduces to that of a long cylinder subjected to a band of linearly varying pressure around its circumference (Fig. 8(c)). This condition may be analyzed using an extension of the approach suggested by Timoshenko and Woinowsky-Krieger (10) for a cylinder subjected to a band of uniform pressure around its circumference. It can be shown (7) that, within the loaded area, at a location defined by the dimensions b and c in Fig. 8, the hoop stress, σ_h, in the wall of the cylinder is given by

$$\sigma_h = \frac{pd}{2t} K \quad [2]$$

where K is given by

$$K = -\{c(e^{-\beta c} \cos\beta c + e^{-\beta b} \cos \beta b - 2)/2\ell + [e^{-\beta c} (\sin \beta c - \cos \beta c - 2\beta \cos \beta c) - e^{-\beta b} (\sin \beta b - \cos \beta b - 2\beta b \cos \beta b)]/4\beta\ell \quad [3]$$

and $\beta^4 = 12(1 - \nu_T^2)/d^2t^2$, ℓ is the thickness of the ice cap, d is the diameter of the cylinder, t is the thickness of the cylinder wall and ν_T is the Poisson's ratio of the cylinder material. The maximum hoop stress occurs at a location defined by $c/\ell \approx 0.667 + 0.01\beta\ell$ and the corresponding value of K from Eqn. [3], K_{max}, is a function of $\beta\ell$ as shown in Fig. 9.

Similar expressions can be developed (7) for hoop stress in the portions of the cylinder wall above and below the ice cap. Flexural stresses in the wall of the cylinder can also be determined in a similar manner (7).

The pressure, p, at the top of the ice cap, corresponding to a particular temperature gradient through the ice cap, may be found by considering compatibility of deformations at the location of maximum deformation in the tank wall. The pressure, for a particular temperature change, is a function of $\beta\ell$ and η as shown in Fig. 10. The parameter η is defined as $E_I d/E_T t$ where E_I and E_T are the moduli of elasticity of ice and tank materials, respectively.

A typical variation of hoop stress in the wall of a tank, as predicted by the above theory, is shown in Fig. 11, which also shows for comparison corresponding variations obtained using the computer program ABAQUS (11) to model the ice cap in the tank but neglecting creep in the ice. An idealized variation of the hoop stress proposed for design purposes is also indicated in Fig. 11. The locations of peak hoop stress and zero hoop stress in the wall of a tank are indicated. The zero stress locations are a function of β and ℓ.

The magnitudes of the peak hoop stress may be determined using Figs. 9 and 10. Figure 10 may be used to determine the pressure in a cylinder of any material containing an ice cap subjected to a known linear temperature gradient throughout its thickness. The related maximum hoop stress can be determined from Eqn. [2] using the relevant value of K_{max} obtained from Fig. 9.

Creep of the ice will reduce the pressure exerted by an ice cap subjected to a rise in temperature over a finite time. The maximum static values of pressure and related hoop stress, determined as described previously, can be adjusted for creep using Fig. 12, which shows the peak pressure developed in the ice as a percentage of the corresponding maximum static pressure which would occur if creep were neglected. Creep effects are dependent on initial temperature, heating rate and η.

Kong and Campbell (8) have shown that, in a concrete tank having a diameter of 7140 mm (23.5 ft.) and a wall thickness of 400 mm (16 in.), a hoop stress in the order of 6 MPa (870 psi) is induced by an ice cap which is heated from a initial temperature of -20°C at a rate of 2°C per hour at the top surface. Such a stress will crack the concrete wall.

DESIGN CRITERIA AND RECOMMENDATIONS

General

From the previous discussions it is clear that no cracks through the wall should be permitted to ensure adequate design life for a tank in a freezing environment. It is recommended that tanks be (a) leakproofed by an interior liner, (b) post-tensioned to provide a residual compression of 1.5 MPa (220 psi) in both vertical and circumferential directions after consideration of all environmental loading and (c) protected