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ELEVATED STORAGE TANKS-WATER TOWERS: LAYOUTS, TYPES AND STRESSES

SKLADIŠNI REZERVOARI NA VISINI-VODOTORNJEVI: KONFIGURACIJE, TIPSKA REŠENJA I NAPREZANJA

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Keywords
- water towers
- hydrostatic pressure
- reinforced concrete
- layout

Abstract

Water towers represent a specific class of elevated structures whose structural integrity is governed by the interaction between geometric configuration, material properties, loading conditions, and long-term degradation processes. Many existing water towers were designed several decades ago and are currently operating beyond their original design life which raises concerns regarding their safety and serviceability under contemporary loading requirements. This paper provides a structured overview of water towers from the perspective of structural integrity and remaining life considerations. Particular emphasis is placed on wind and seismic loading effects, material behaviour, and assessment challenges relevant to existing structures. Typical structural configurations and materials are reviewed, and key issues related to inspection, analysis, and integrity evaluation are discussed. The paper aims to support engineers and researchers involved in the assessment and maintenance of water towers by highlighting critical aspects influencing their structural performance and long-term reliability.

Ključne reči
- vodotornjevi
- hidrostatički pritisak
- armirani beton
- konfiguracija

Izvod

Vodotornjevi predstavljaju posebnu klasu izdignutih konstrukcija čiji je integritet konstrukcija određen međusobnim delovanjem geometrijske konfiguracije, svojstava materijala, uslova opterećenja i dugoročnih procesa degradacije. Mnogi postojeći vodotornjevi projektovani su pre nekoliko decenija i danas funkcionišu izvan svog prvobitno predviđenog projektnog veka, što otvara pitanja njihove bezbednosti i upotrebljivosti u savremenim uslovima opterećenja. Ovaj rad daje strukturisan pregled vodotornjeva sa aspekta integriteta konstrukcije i razmatranja preostalog radnog veka. Poseban naglasak stavljen je na dejstvo vetra i seizmičkih opterećenja, ponašanje materijala i izazove procene postojećih konstrukcija. Razmatraju se tipične konfiguracije konstrukcija i korišćeni materijali, kao i ključni problemi vezani za inspekciju, analizu i ocenu integriteta. Cilj rada je da pruži podršku inženjerima i istraživačima koji se bave procenom i održavanjem vodotornjeva, ukazujući na kritične faktore koji utiču na njihovo konstrukcijsko ponašanje i dugoročnu pouzdanost.

INTRODUCTION

Storage tanks installed at an elevated height are most commonly used for water storage and are therefore referred to as water towers. The first written records related to the construction of water towers can be found in the prospectuses of the Chicago Bridge & Iron (CB&I) Company dating back to 1912.

A water tower is an elevated structure that supports a water tank positioned at a height sufficient to pressurize a potable water distribution system and to provide emergency storage for fire protection. Water towers often operate in conjunction with underground or surface service reservoirs that store treated water close to the point of consumption. Other types of water towers may be used exclusively for storing raw (non-potable) water intended for fire protection or industrial purposes and are not necessarily connected to a public water supply network.

Water towers are capable of supplying water during power outages because they rely on hydrostatic pressure generated by the elevation of water due to gravity. This pressure enables water to flow into domestic and industrial distribution systems without the immediate need for pumping. However, water towers cannot supply water indefinitely without power, as pumps are typically required to refill the tank. In addition, a water tower serves as a buffer reservoir that helps meet increased water demand during peak usage periods. The water level in the tower usually decreases during daytime peak consumption and is replenished by pumping during nighttime hours. This continuous draining and refilling process also reduces the risk of freezing in cold climates /1, 2/.

Most water towers have heights ranging from approximately 130 to 165 feet (40-50 m). They are often located on elevated ground to provide sufficient pressure for municipal water supply systems, ensuring adequate service to all consumers within the distribution area. A typical water pressure increase of about 0.43 psi (pounds per square inch) is provided for every foot of elevation in a water tower.

The storage tank of a water tower is typically large, with capacities of 1,000,000 gallons (approximately 4,000,000 litres) of water or more. In general, water towers are designed to store at least one day's worth of water for the communities or industrial facilities they serve, /3/.

Considering that water towers are elevated structures used for water storage and distribution since Roman times, the materials used for their construction, as well as their structural layouts and shapes, have been continuously modified and improved. Accordingly, the main objective of this article is to analyse the materials currently used for water tower construction and their structural configurations from the perspective of modern automated systems and instrumentation. In addition, available structural shapes are presented, many of which represent notable architectural achievements.

AN OVERVIEW OF HISTORICAL DEVELOPMENT

A water tower is a tank whose bottom is elevated above ground level. Such a structure primarily consists of two main parts: the tank itself, also referred to as the reservoir, located in the upper part of the structure, and the supporting structure or base, forming the lower part. In addition to these basic elements, a water tower must include provisions for water supply and discharge, as well as overflow and drainage pipelines, access facilities to the tank, and ventilation systems (Fig. 1).

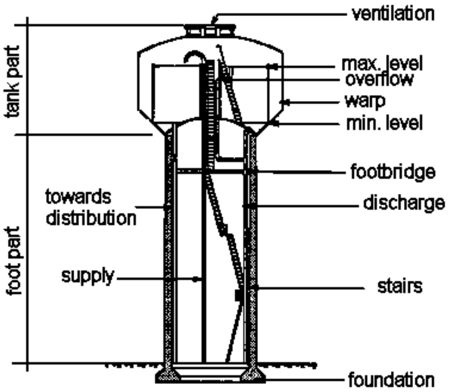


Figure 1. Older construction of a water tower, /4/.

Within the water supply system, a water tower fulfils a dual function. First, it acts as a buffer between water production, which is preferably carried out as uniformly as possible, and water delivery to consumers, which follows a daily cycle characterised by peak demand during the day and minimal consumption during the night. Second, it must ensure a minimum pressure at all points of the distribution network.

These functions are closely related to the origins of potable water distribution through networks which date back to the middle of the last century. Previously, the role of water towers was more limited and primarily related to water distribution. As early as Roman times, water conveyed by aqueducts supplying cities was collected in a *castellum aquarum*, an elevated reservoir from which water was distributed to different districts. In Nîmes, this castellum had the form of a cylindrical tank from which ten lead pipes extended. In Pompeii, water was distributed from a central water tower to smaller water towers dispersed throughout the city, supplying various districts either through continuously operating public fountains or through a distribution network serving private houses. These water towers consisted of a masonry base supporting a monolithic tank.

This simple design remained in use until the nineteenth century. For example, districts of the city of Liège were supplied with water as early as 1690 via water towers that served a similar distribution function to those used in Pompeii. The water tower of the Roland Fountains consisted of a brick tower containing a copper tank with a diameter of 80 cm and a depth of 45 cm, from which lead pipes extended to supply private fountains and household connections. In Liège, water could be conveyed by gravity due to the elevated galleries located in the Meuse valley. In flat regions, such as Flanders and the Netherlands, water had to be pumped prior to distribution.

In the fifteenth century, the use of elevated tanks could be avoided in hydraulic buildings in Bruges, as water was conveyed to the city centre via running water fountains. Around 1550, water supplied to breweries in Nieuwstad, Antwerp, was delivered intermittently. A horse-driven mechanism was used to pump water into an elevated tank, from which lead pipes supplied individual breweries. Water was delivered upon payment by opening the supply valve of the respective brewery. Although the distribution function of the water tower remained dominant in this case, the importance of water storage capacity became evident.

This storage function became even more significant after 1835, when the development of railway networks based on steam traction began. Steam locomotives required frequent supplies of large quantities of water in a short time which could not be achieved solely by pumping. The solution involved the installation of elevated tanks. Water towers in the modern sense of the term were rarely constructed; instead, iron or wooden tanks were often installed on the upper floors of ordinary buildings. This explains why water towers are seldom visible in panoramic sketches of railway stations from that period. Pumps required for filling the tanks were typically located on the ground floor. At that time, potable water supply in rural areas was insufficiently developed to serve these installations, leading railway companies to undertake water provisioning themselves - an activity that, in some cases, continues to the present day.

The development of modern potable water supply systems assigned water towers their current functions as storage buffers and automatically regulated pressure control elements. These functions determine the required storage capacity and installation height. Storage capacity is derived from the difference between water supply from production units and water demand in the distribution network. This requires knowledge of daily demand fluctuations and estimation of future consumption trends. Additional demand for fire protection and emergency storage requirements in case of production failure must also be considered.

The elevation of the water reservoir is determined by the minimal pressure required at critical points of the distribution network, as well as by pressure losses in pipelines. Based on a study of local topography and pipeline network layout, the most suitable location for the tank and the required tower height can be determined.

The external appearance of a water tower is initially defined by design requirements, particularly tank capacity and elevation. Subsequently, the availability of construction materials and advances in civil engineering have played a significant role. Between 1880 and 1910, improvements in iron tank construction strongly influenced the appearance of water towers, while the introduction of reinforced concrete and later prestressed concrete significantly affected their more recent development. Economic considerations are closely linked to these technological advances. The reduction in base dimensions, made possible by the introduction of the Intze foundation system toward the end of the nineteenth century, led to substantial cost savings due to reduced masonry volume. More recently, the transition from masonry column-type towers to concrete mushroom-shaped towers was also driven by differences in construction methods and costs, particularly with the use of sliding formwork.

It is evident that the use of decorative elements increases the cost of water towers. In Belgium, unlike in countries such as Germany and the Netherlands where cities constructed monumental water towers, relatively limited resources were devoted to architectural embellishment. With the transition to concrete construction, a utilitarian but stereotypical style emerged, which is often perceived as unaesthetic. In response to this trend, a design competition for water towers suitable for small towns and rural communities was organised in France in 1939. Analysis of submitted projects indicates that:

- conical form was abandoned in favour of cylindrical tanks;
- domed roofs were replaced by high conical roofs or flat roofs with mansard-type superstructures;
- architectural elements were introduced to improve the visual appearance of towers, including:
  - bases thinner than the tank, reinforced by pseudo-ribs;
  - polygonal bases combined with cylindrical tanks;
  - solid walls replaced by colonnades at circular or polygonal levels.

These design elements, introduced in France, subsequently influenced the construction of water towers in Belgium until the 1970s. Another important factor affecting the external appearance of water towers was the prevailing architectural style of the period. Toward the end of the 19th century, neo-classical and eclectic elements were common. At the beginning of the 20th century, Art Nouveau influences appeared through the use of coloured brick facades, while often elaborate decoration of the 1930s reflected Art Deco trends. In this context, the historical development of water tower construction in Belgium can be outlined. It was shaped both by trends originating abroad, particularly in France and Germany, and by local characteristics that, in turn, influenced water tower construction in other countries, /4/.

CONFIGURATION AND AUTOMATIC SYSTEM

From the standpoint of automation level, water tower systems can generally be classified into the following concepts: basic (typical configurations); modern (using PLC-based control systems).

In a typical configuration (Fig. 2), water is pumped and stored in the tank by a high-pressure water pump, while an electromechanical or manual valve releases water to consumers when required, /5/.

It should be highlighted that telecommunication companies very often install their equipment at the tops of water towers (Fig. 3), /6/.

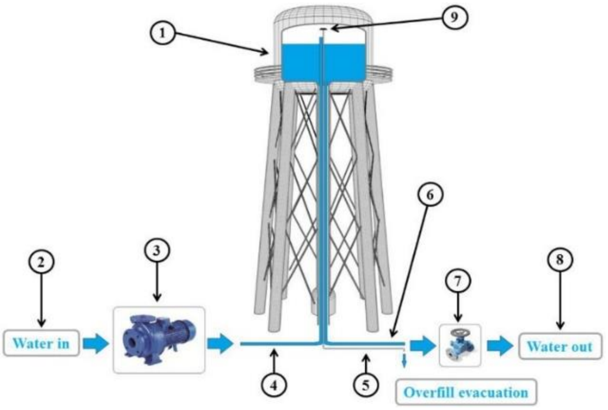


Figure 2. Water tower typical layout: 1-tank; 2-sources; 3-pump; 4-inlet pipe; 5-tank overfill/pressure relief pipe; 6-outlet pipe; 7-regulation valve; 8-water distributed to consumers; 9-tank overfill level cap valve, /5/.

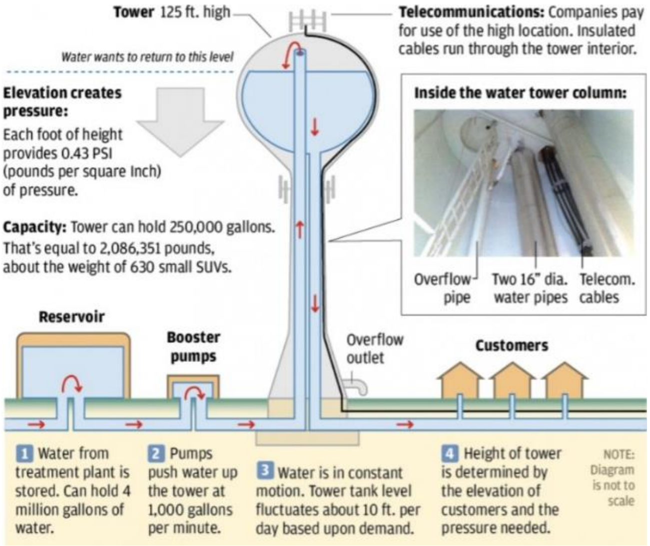


Figure 3. Water tower with telecommunication equipment, /6/.

In contrast to the basic concepts, modern water tower systems use PLC-based equipment as the main control system for managing the water distribution process (Fig. 4). In addition to water pumps and valve regulators, upgrading a water tower system to include electrical power generation typically involves the installation of the following electrical and

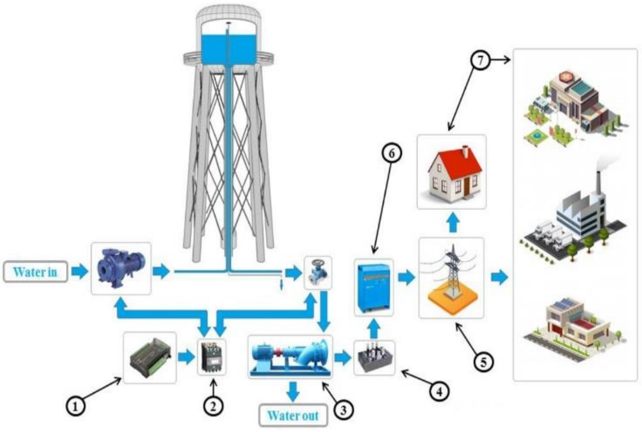


Figure 4. Water tower – modern layout: 1 industrial PLC, 2 power relays, 3 hydroelectric power generator, 4 AC-to-DC regulator, 5 electrical grid, 6 DC-to-AC inverter, 7 consumers.

automation components:
- three-phase water turbine generator;
- AC-to-DC regulator;
- DC-to-AC inverter;
- industrial PLC (Programmable Logic Controller) with a Real-Time Clock (RTC);
- power relays, wiring, and junction boxes.

It should be noted that the Real-Time Clock (RTC) is a timekeeping circuit integrated into a PLC to maintain accurate date and time information, even when the main power supply is switched off, /5/.

Generally, two operating configurations can be distinguished for modern (upgraded) water tower systems, depending on storage capacity and hydroelectric power output:
- as a standalone off-grid backup generator (for output < 10 kWh/day);
- as an additional on-grid generation unit (for output > 10 kWh/day).

In both configurations, the water tower can be operated through the programmable logic controller to generate hydroelectric energy either on demand or during pre-programmed time periods using the real-time clock:
- during nighttime, when solar energy is not available (off-grid configuration), with the tank refilled during daytime when excess solar energy is available;
- during daytime peak demand periods (on-grid configuration), with the tank refilled at night when electrical energy costs are lower.

For upgrading water tower systems, appropriate theoretical calculations are usually required. System dimensioning involves the calculation of energy conversion efficiency of the components, electrical power ratings as a function of time, and flow rates correlated with the usable volume of the water tower, /5/.

MATERIALS AND LIFE SPAN

Materials most commonly used for water tower construction are wood, reinforced concrete, steel, composite materials /7-9/.

The first material used for the construction of water towers was wood. At the time, particularly in the United States, wooden water towers were widely used as a primary means of water distribution. In the 1800s, as buildings in New York City grew taller than six stories, the existing water infrastructure was unable to provide sufficient water pressure. Water towers were therefore introduced to safely supply water to floors above the sixth level. Today, there are approximately 10,000 to 15,000 functioning water tanks in New York City. Simple in construction, these water tanks are usually made of wood. Wood acts as a natural insulator and helps prevent water from freezing during winter conditions. No sealants or chemicals are used to avoid contamination of the water supply, /7/.

Reinforced concrete water towers represent a newer construction type compared to wooden towers. These towers are usually built with capacities of up to approximately 5,000 m^3. Such structures are often designed in cooperation with architects, allowing functional requirements to be combined with architectural considerations.

Steel water towers originated from relatively small welded tanks and have been used for over 100 years, particularly in industrial applications and railway transport. Early designs typically consisted of small-radius cylindrical tanks supported by a framework of steel columns with bracing or tie members. Today, welded steel water towers with capacities of up to 15,000 m^3 are available and have been widely used worldwide, particularly in North America, the Middle East, and the Far East, /8/.

Composite water towers (CSTs), also referred to as composite elevated water tanks or concrete pedestal elevated tanks, consist of a welded steel tank for watertight containment, a single reinforced concrete pedestal support structure, a foundation, and associated accessories. The steel tank provides a proven watertight container derived from the AWWA D100 standard for welded steel tanks, which has demonstrated reliable performance over decades of use in the water industry. The reinforced concrete support column provides a cost-effective and structurally robust pedestal requiring minimal maintenance, /10/.

In addition to the previously mentioned aspects, the maximal life span, average capacity, and fabrication costs of water towers in relation to the construction material are presented in Table 1, /7, 9/.

Table 1. Water tower: material vs. general data.

Material	Average capacity	Life span	Cost range
Wood	5000 gallons	30 years	\$5K-\$30K
Concrete	1-5 million gallons	150 years	\$1M–\$3M
Steel	500000-2 million gal.	100 years	\$500K–\$2M
Composite	500000-3 million gal.	75 years	\$700K–\$2M

Water towers frequently become iconic elements of the landscape. They often serve as symbols of local identity and heritage and are commonly decorated with distinctive designs. Their prominent presence highlights the essential role they play in everyday life and infrastructure systems, /9/.

DESIGNS (SHAPES) OF WATER TOWERS

Water towers, as discussed in the previous chapter, are usually constructed from wood, reinforced concrete, steel, or composite materials, /7, 9/.

Wooden water towers are typically cylindrical in shape, with wooden elements installed adjacent to one another along their longitudinal sides. Depending on the design, roofs usually belong to the conical roof type (Fig. 5), /11/.

Figure 5. Water tower in New York City, USA, /11/.

Reinforced concrete water towers are commonly constructed in the following configurations:

- rectangular reinforced concrete water towers;
- circular reinforced concrete water towers;
- concrete cone-shaped water towers;
- concrete sphere-shaped water towers;
- disk-shaped water towers;
- concrete mushroom-shaped water towers;
- reinforced concrete water towers with specific or unconventional shapes, /1, 8/.

Rectangular reinforced concrete water towers are usually designed as relatively small monolithic service reservoirs, with the floor slab supported on an open column-and-beam framework or a hollow vertical shaft founded on a base slab, piled if necessary. Wind and seismic loads must be considered in the design of the tank, supporting structure, and foundation system (Fig. 6), /8/.

Figure 6. Rectangular reinforced concrete water tower, /12/.

Reinforced concrete circular water towers are more commonly constructed than rectangular concrete towers. The diameter of circular water towers is usually not sufficient to require prestressing, as cracking can be controlled using standard water-retaining concrete design criteria. Circular concrete water towers allow greater architectural flexibility, and their appearance may be regarded as a visual asset. Typical dimensions adopted for reinforced concrete circular water tower design are presented in Table 2 and illustrated in Fig. 7, /8/.

Table 2. Typical dimensions of concrete circular water towers, /8/.

No.	Size (m^3)	Depth of water(m)	Internal diameter (m)
1	1200	7.5	17.0
2	2000	9.1	19.4
3	3000	10.2	22.6

Reinforced concrete circular water towers allow a wide range of architectural forms, from simple cylindrical shapes with flat bases to more complex geometries such as hyperbolic paraboloids. In such cases, the vase-like shape may resemble an inverted version of nearby control towers.

A more recent variation of circular water towers is the Intze-type water tower (Fig. 8). These towers are designed so that bending moments are minimised across structural sections. Radial thrusts from the outer conical base section balance those from the spherical central section. Roofs may be flat for small tanks, conical, or spherical for larger tanks, while bottom heads may be circular or domed, /8, 13/.

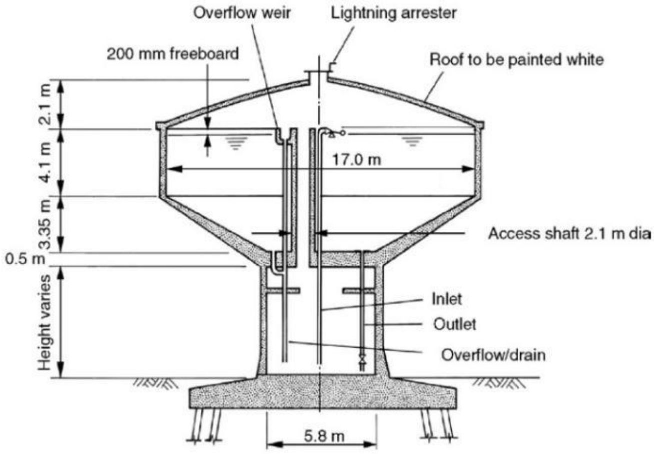


Figure 7. Reinforced concrete circular water tower, /8/.

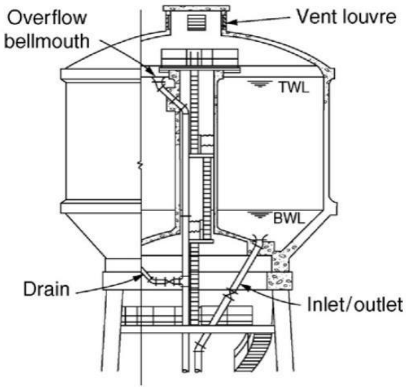


Figure 8. Intze-type circular water tower /8/.

One of the main advantages of the Intze-type water tower is that large-capacity circular tanks become more economical compared to flat-bottom designs. Generally, an Intze tower consists of a top dome supported on a ring beam resting on a cylindrical wall. This wall is supported by ring beams and a conical slab. A bottom dome is also provided and supported by a ring beam. The conical slab and bottom dome are supported by a circular beam, which in turn is supported by a number of columns. For large storage capacities, the tank may be divided into two compartments by partition walls supported on a circular beam. An Intze-type water tower in service condition is shown in Fig. 9, /13/.

Figure 9. Intze water tower in service condition, /13/.

The conical slab in Intze-type towers is designed to resist hoop tension resulting from water pressure. This slab spans between the upper ring beam and the lower ring girder. The ring girder supports the tank and its components and is supported by columns braced at intervals to resist bending moments and torsional effects. The columns are designed to carry the total transferred load and are braced at regular intervals to resist wind or seismic loads, depending on site conditions.

Reinforced concrete cone-shaped water towers are relatively rare compared to circular water towers. Figure 10 shows one of the most well-known water towers in the Balkan region, located in Vukovar, Croatia, /14/.

Figure 10. Cone-shaped water tower, Vukovar, Croatia, /14/.

Figure 11. The main water towers in Kuwait City, /16/.

Figure 12. Visit of Yugoslav President Josip Broz Tito during the final construction phase, /17/.

Concrete sphere-shaped water towers are also rare in water distribution systems. Figure 11 presents the water tower system located in downtown Kuwait City. These towers were designed by the Danish-Swedish architects Malene Bjørn (1914-2016) and Sune Lindström (1906-1989), /15/. Construction was performed by RAD Holding Company from Belgrade, Yugoslavia. The towers were put into service on 26 February 1977, while the restaurants were opened to the public on 1 March 1979, /16/. In addition to Fig. 11, which shows the Kuwait Towers in service, Fig. 12 presents a visit by Yugoslav President Josip Broz Tito during the final phase of construction on 2 February 1979, /17/.

The water tower system consists of three towers. The main tower is 187 m high and consists of two spheres. The lower sphere contains a water tank with a capacity of 4,500 m^3 in its lower half, while the upper half includes a restaurant, rest areas, and a reception hall. The upper sphere rises 123 m above sea level and includes an observation deck rotating once every 30 minutes. The second tower, 147 m high, also serves as a water tower. The third tower houses equipment for flow control and illumination of the two higher towers. Together, the system stores approximately 9,000 m^3 of water. The towers were damaged during the Iraq-Kuwait war in 1991; however, the most significant damage affected electrical installations, /15, 16/.

Disk-shaped water towers are rarer than previously described types and are typically used in systems requiring lower storage capacities. Figure 13 shows a disk-shaped water tower in Mechelen, Belgium.

Figure 13. Concrete disk-shaped water tower, /18/.

Mushroom-shaped water towers are commonly found in water distribution systems. Finland, in particular, has a large number of such structures. Figure 14 shows the Lauttasaari water tower in Helsinki, Finland, which was the first mush

Figure 14. Lauttasaari mushroom shaped water tower, /19/.

room-shaped water tower in the country and is considered architecturally and historically significant. The tower was designed by architect Ossi Leppämäki (1918-2009), /18, 19/.

The general structure of Lauttasaari water tower is shown in Fig. 15 and is representative of this type of construction /19/.

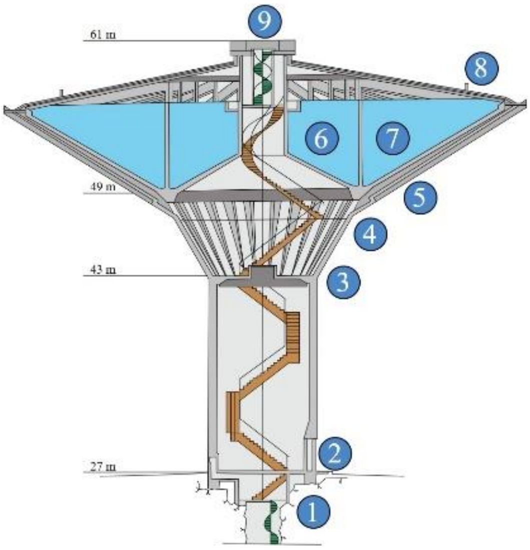


Figure 15. Cross-section of the Lauttasaari water tower: 1-shaft and stairs to the water tunnel; 2-front door; 3-central opening for supply lifting; 4-central room and support beams; 5-support ring; 6-inner water container; 7-outer water container; 8-air-conditioning pipes; 9-roof platform.

Figure 16. Hyllie water tower, Malmö, Sweden, /21/.

Kuwait also has a large number of concrete mushroom-shaped water towers which form the main components of its water distribution system, /20/. Other specific water tower designs also exist, with shapes often determined by municipal or private requirements. Figure 16 shows a spaceship-shaped water tower in Malmö, Sweden, /21/.

Steel (welded) water towers have been used for over 100 years in industrial applications, water distribution systems, and railway transport. Early designs typically consisted of small-radius cylindrical tanks supported on steel column frameworks with braces or ties. Today, welded steel water towers with capacities of up to 15,000 m^3 are widely used worldwide, particularly in North America, the Middle East, and the Far East. These towers are commonly constructed in the following configurations, /8/:

- rectangular steel water towers;
- spheroidal tanks on tubular columns with flared bases;
- ellipsoidal tanks on tubular columns with flared bases;
- cylindrical water towers;
- spherical water towers;
- polyspheroid water towers;
- toroidal water towers;
- mushroom-shaped water towers;
- steel water towers with specific or unconventional shapes.

Rectangular steel water towers are commonly used in desert regions for potable or technical water distribution. Figure 17 presents a rectangular galvanised steel water tank installed in a desert environment.

Spheroidal steel water towers are frequently used in industrial plants and water distribution systems. Figure 18 shows the Red Deer AB Water Tower 2, Alberta, Canada.

Ellipsoidal water towers are commonly used for water distribution in industrial facilities. Figure 19 presents the Kohler ellipsoidal water tower located near the Kohler Company facilities, /24/.

Figure 17. Rectangular steel water tower, /22/.

Figure 18. Red Deer AB Water Tower 2, Alberta /23/.

Figure 19. Kohler ellipsoidal water tower, Wisconsin, /24/.

Cylindrical steel water towers are used in industrial plants and water distribution systems where lower storage capacities are required. These towers may have flat or domed heads, while bottom heads are often torispherical and roofs may be conical. Figure 20 shows a cylindrical steel water tower with a conical roof and torispherical bottom head.

Spherical steel water towers were historically used in railway transport for supplying water to steam locomotives. These towers were typically installed on specially shaped concrete supports. Figure 21 shows a representative example installed near the Gazela Bridge in Belgrade, Serbia.

Today, spherical steel water towers are typically supported by tubular columns and are used for water distribution in industrial facilities or urban environments. Figure 22 shows the Harrison spherical water tower during an external cleaning operation.

Figure 20. Cylindrical steel water tower with conical roof, /25/.

Figure 21. Spherical steel water tower, Gazela Bridge, /26/.

Figure 22. Spherical steel water tower during cleaning, /27/.

Personnel performing cleaning operations on these tanks must possess appropriate certification for working at height, such as IRATA certification.

Polyspheroid water towers represent an unusual tower configuration and are most commonly found in the United States. Figure 23 shows a polyspheroid water tower used for water distribution in San Diego.

Toroidal water towers are rarer than spheroidal and spherical designs. Their support structures often consist of hyperboloid lattice systems, which maximize structural strength while minimizing material usage. One of the most well-known examples is the Ciechanów water tower, constructed in 1972 in Poland (Fig. 24), /29/.

Figure 23. Polyspheroid water tower in San Diego, /28/.

Figure 24. Toroidal steel water tower in Poland, /29/.

Figure 25. Mushroom-shaped steel water tower, /30/.

Mushroom-shaped steel water towers are a modification of classical water tower design and are more commonly used in urban water distribution systems than in industrial applications. Figure 25 shows a representative example.

Steel water towers with specific or unconventional shapes can be fabricated to meet municipal or private requirements, similar to concrete water towers. Examples of such designs are shown in Figs. 26-30.

Composite water towers, or composite elevated water tanks, consist of a welded steel tank for watertight containment, a reinforced concrete pedestal support structure, a foundation, and associated accessories. These structures are also referred to as concrete pedestal elevated tanks. The steel tank is designed in accordance with the AWWA D100 standard and provides a proven watertight solution widely used in the water industry. The reinforced concrete pedestal offers a cost-effective and structurally robust support requiring minimal maintenance. Typical composite water tower configurations are shown in Fig. 31, /10/.

Figure 26. Corn shaped water tower in Minnesota, /31/.

Figure 27. Peachoid water tower in South Carolina, /32/.

Figure 28. Swedish coffee pot water tower in USA, /33/.

Figure 29. Bottle water tower in Collinsville, Illinois, /34/.

Figure 30. Watermelon water tower in Texas, /34/.

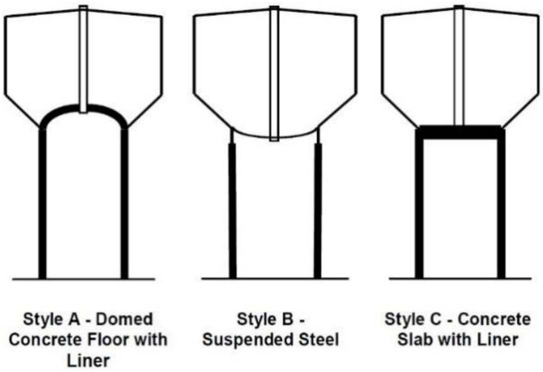


Figure 31. Composite water towers-types, /10/.

The most common composite elevated water tank configuration consists of a domed concrete floor with a carbon steel liner (Style A). Figure 32 shows a composite water tower after commissioning.

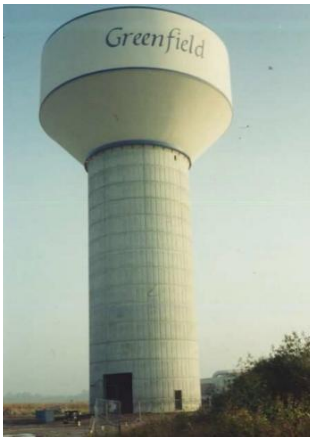


Figure 32. Composite water tower in service, /10/.

DISCUSSION

Before the fabrication or construction of any process equipment or industrial plant, a comprehensive technical analysis accompanied by a cost-benefit assessment is usually performed. In the same manner, such an analysis is carried out prior to the construction of a water tower system. Within this comprehensive evaluation, all advantages and disadvantages of water towers are analysed. Main advantages of water towers include:

- water towers facilitate maintaining consistent pressure in public water supply systems, which is otherwise difficult to achieve;
- water towers provide a reliable reserve of water to cope with periods of peak demand;
- provided that the water tower is sufficiently elevated, water distribution can be achieved solely through hydrostatic pressure driven by gravity;
- the installation of a water tower reduces the need for high-capacity pumping systems designed to meet peak demand;
- water towers reduce the number of pumping stations required within a region and allow centralisation of pressurisation and pumping;
- water can be pumped to the tower during off-peak periods, reducing operational costs associated with pump operation;
- from an electrical engineering standpoint, water towers may be considered a form of pumped hydroelectric energy storage (PHES) and can be used for electrical load balancing during peak electricity demand;
- one of the key advantages of water towers lies in their simple construction concept, requiring only a water source (which may be recirculated in some cases), a pump for water supply through the inlet pipe, an overflow pipe or valve to prevent overfilling, a storage tank, an outlet pipe for water discharge, and valves for regulating inlet and outlet flow;
- water towers represent a practical solution for supplying water to flat cities and settlements;
- a major advantage of water towers is their ability to utilise multiple water intake sources, including lakes and rivers, groundwater, underground reservoirs and wells, local water distribution networks, or even rainwater collected from specific areas.

On the other hand, the main disadvantages include:

- even the most efficient water tower cannot completely prevent minor pressure drops during sudden demand surges;
- water can only flow to areas located at lower elevations than the water tower, limiting application in hilly terrain;
- water towers may temporarily affect the taste and odour of water, particularly during the initial months of operation;
- untreated water towers may accumulate bacterial layers and sludge, requiring cleaning at least every three years;
- decommissioned water towers are often neglected by municipal authorities or private stakeholders due to lack of interest, vision, or funding, resulting in demolition, abandonment, conversion into architectural landmarks or dwellings, or repurposing as cellular towers.

In addition to the advantages and disadvantages discussed above, wind and seismic effects must be considered when making decisions regarding the construction of water towers. These effects are typically analysed using numerical simulations and finite element (FE) methods. FE models are commonly subjected to linear modal (frequency) analysis to predict the fundamental vibration modes of the structure, either with an empty tank or as a coupled fluid-structure system, and to assess corresponding frequencies and mode shapes, /35/.

For seismic assessment of similar systems, it is well established that the fundamental vibration mode plays a dominant role in structural behaviour under horizontal seismic excitation, /36/. Consequently, primary attention during FE model calibration should be focused on the first vibration mode. Higher modes generally have low modal participation factors and are less influential in predicting the response of elevated tanks to horizontal base motions. Nevertheless, accurate model calibration should be based on validation of multiple vibration modes, including both frequencies and mode shapes.

Such analyses are commonly conducted using software packages such as SAP2000 or ABAQUS. Figure 33 presents the results of a modal analysis of a water tower with an empty tank performed using SAP2000.

Figure 34 shows the results of a corresponding analysis performed using ABAQUS.

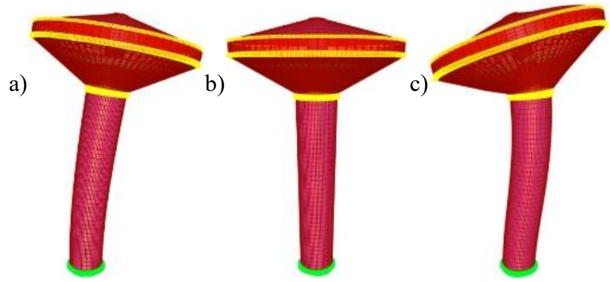


Figure 33. Fundamental vibration shapes for the structural modes of the tank with empty container (in SAP2000): a) mode 1 (1st flexural); b) mode 2 (torsional); c) mode 3 (2nd flexural).

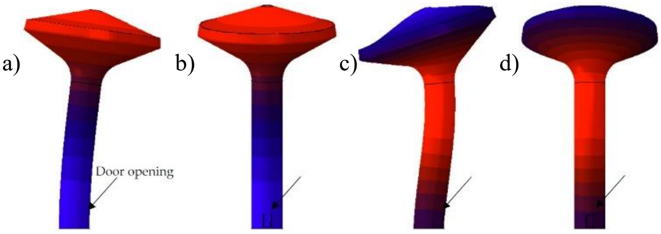


Figure 34. Fundamental vibration modes of the water tower with an empty tank obtained using ABAQUS: a) mode 1 (1st flexural), side view; b) mode 1 (1st flexural), front view; c) mode 3 (2nd flexural), side view; d) mode 3 (2nd flexural), front view.

Based on analysis results, it can be concluded that the results obtained using ABAQUS are more precise and reliable compared to those obtained using SAP2000. One of the reasons is that ABAQUS allows more detailed modelling of geometric features, such as door openings which can be included directly in the structural model. Presence of door openings in the water tower support results in minor symmetry loss in the dynamic response and introduces negligible local deformation effects, /35/.

Figure 35 illustrates the influence of wind loading in a general case. Wind effects are typically treated as horizontal loads, and the corresponding support reactions are also shown.

From a fluid mechanics perspective, wind effects around water towers correspond to natural and forced convection around isolated bodies, where flow patterns depend on the tower geometry. Figure 36 presents flow patterns around an isolated sphere as a function of Reynolds number, /37-40/.

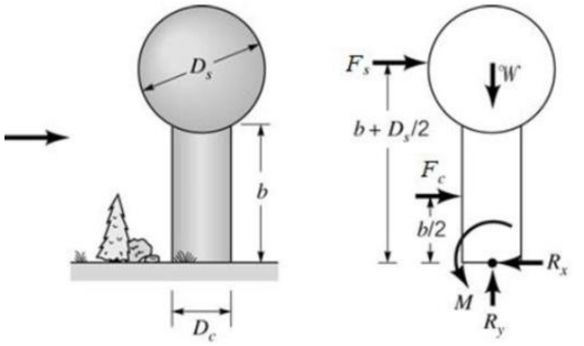


Figure 35. External drag on water towers, /38/.

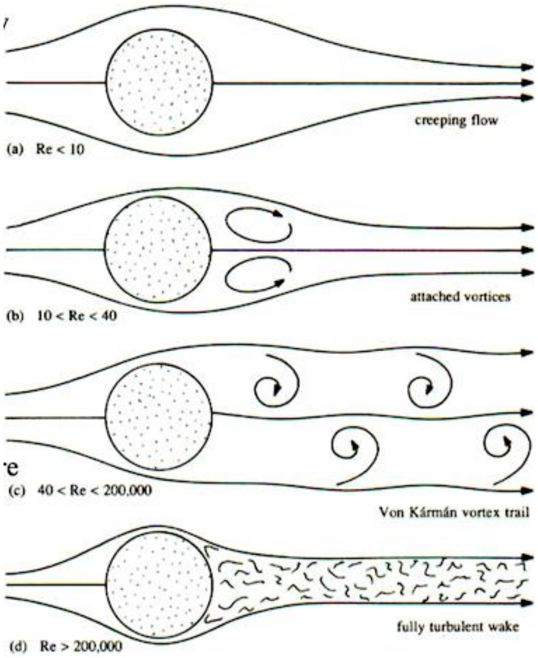


Figure 36. Flow images vs. Reynolds number, /38/.

Similar flow characteristics may be expected for other water tower geometries. From a thermodynamic standpoint, water towers may be treated as isolated objects exposed to natural and forced convection in a large, effectively infinite volume under varying weather conditions. For such analyses, an appropriate equivalent diameter should be estimated.

Unlike conventional building structures, where applied actions remain relatively constant over time, water towers experience significant variations in loading during operation. The total weight of an empty water tower may be reduced to approximately 20 % of its fully filled condition. This variation in gravity load complicates seismic design. Moreover, water towers generally lack structural redundancy and alternative load paths. During strong seismic events, even if the tank itself remains intact, damage to the supporting structure may lead to collapse due to low redundancy and limited ductility, /41/.

Currently, most water towers are constructed from reinforced concrete or steel. Comparative studies indicate that reinforced concrete water towers exhibit relatively high load-bearing capacity and flexural stiffness; however, they typically show limited ductile behaviour. Ductility in reinforced concrete water towers is primarily achieved through yielding of flexural reinforcement in the tower shaft and the formation of plastic hinges, /42/.

Several seismic mitigation strategies have been proposed to reduce damage and prevent collapse of water towers. One approach involves increasing load-bearing capacity and stiffness by increasing dimensions and reinforcement; however, this may also increase seismic demand due to higher stiffness. An alternative strategy is to reduce seismic effects through energy dissipation mechanisms.

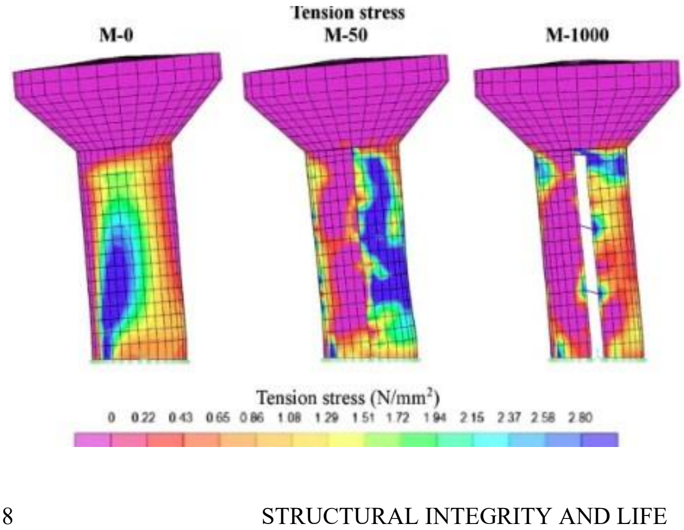
Extensive research has been conducted to enhance the ductility of shear walls subjected to seismic loading, leading to development of practical solutions aimed at redistributing energy demand along the height of the wall. In the early 1970s, the slit shear wall was introduced as an improved system to enhance lateral force resistance. The presence of slits and connectors increases ductility and seismic energy dissipation.

Subsequent studies have shown that slit shear walls exhibit increased ductility compared to conventional shear walls without compromising load-bearing capacity. Although this technique has been widely studied for shear walls, its application to water tower structures has been limited.

The slit shear wall concept applied to water tower design represents an innovative approach aimed at reducing seismic effects by distributing deformation more uniformly along the shaft height. This may reduce ductility demand at the base without sacrificing load-bearing capacity. The proposed slit water tower system has been analysed using finite element methods to verify its nonlinear seismic performance, and the results provide valuable guidance for the design of water towers in seismic regions, /42/.

Overall, this strategy represents a promising solution for the design of reinforced concrete water towers and may also be applicable, with reasonable approximation, to steel water towers, considering the inherently ductile nature of steel.

Figure 37 shows a reinforced concrete water tower during finite element analysis, illustrating load distribution within the structure.



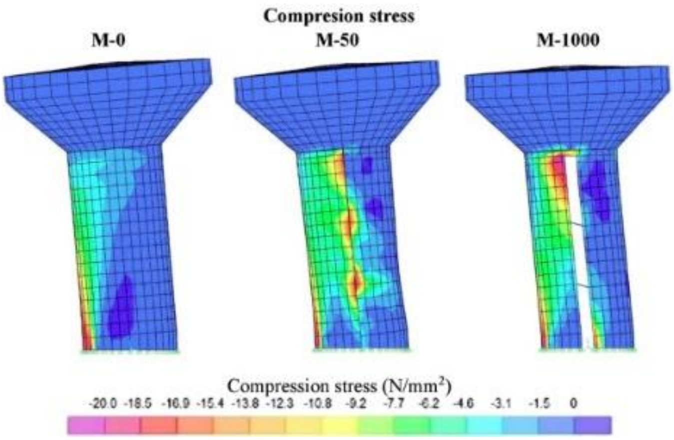


Figure 37. Water tower-loadings distribution, /38/.

CONCLUSIONS

This paper addresses water tower systems which historically played a crucial role in railway transport as essential infrastructure for steam locomotives, while today they represent a key component of water distribution systems in urban areas and municipalities, particularly in regions such as the Middle East and the Far East.

The study presents an overview of both basic and modern water tower configurations, including systems equipped with programmable logic controllers (PLCs) that function as the central control element of modern water tower operation. Water towers are classified according to the construction materials used, and representative structural solutions are discussed for each material category.

The advantages and limitations of water tower systems are examined, together with the types of structural and operational assessments required during design and construction. Special emphasis is placed on the role of numerical analyses which are nowadays predominantly performed using finite element software such as ABAQUS or similar tools.

Based on numerical analysis results, it can be concluded that wind and seismic actions play a dominant role in the structural design of water towers, directly influencing the selection of materials, structural configurations, and suitability of specific solutions for given environmental conditions. The variability of operational loads, combined with limited structural redundancy, further increases the importance of accurate dynamic and seismic assessment.

In seismic regions, an appropriate balance must be achieved between structural capacity and material behaviour. While ductile materials such as steel offer favourable seismic performance, they are typically employed for water towers with lower storage capacities. Reinforced concrete structures, although providing higher stiffness and load-bearing capacity, require careful consideration of ductility and energy dissipation mechanisms to ensure satisfactory seismic performance.

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Appendix - Water tower collapses

Figure A1. Collapse of a 700 m^3 reinforced concrete water tower due to poor-quality materials in Bankura, India, /43/.

Figure A2. Collapse of a steel water tower due to a tornado in Texas, USA, in 2015, /44/.

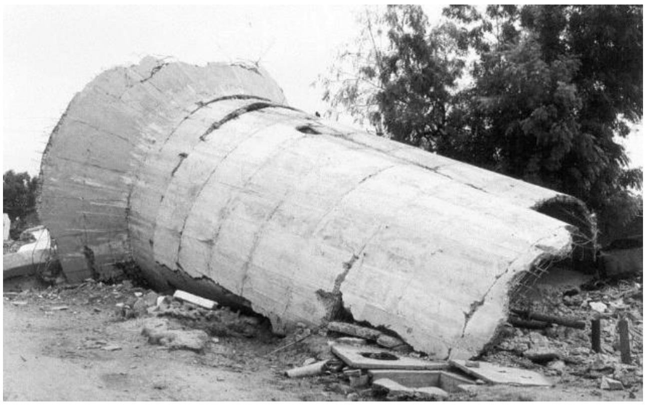

Figure A3. Collapse of a 265 kL water tower in Chobari village (India), approximately 20 km from the earthquake epicentre, /45/.