EVALUATION OF THE DAMPING POTENTIAL OF WATER SUPPLY TANKS DUE TO DYNAMIC WIND-INDUCED RESPONSES IN CONCRETE BUILDINGS

Pedro José Furlani Vidal

Tereza Denyse de Araújo

pedrofurlani@hotmail.com

denyse@ufc.br

Universidade Federal do Ceará

Departamento de Engenharia Estrutural e Construção Civil. Campus Universitário do Pici, Bloco 710, 60455-760, Fortaleza, Ceará, Brazil

Abstract. *Understanding as each structural element contributes to the dynamic behavior of the structure is important for a correct building design. Water supply projects in Brazil place water tanks at the top of structures. A large concrete substructure full of water placed over the roof of buildings may affects global lateral displacement, either by amplifying horizontal motion or by acting as an auxiliary damping system known as tuned liquid damper (TLD). These effects are verified analyzing a 14-storey concrete construction and its reservoir. Modeling of the building and the water reservoir are made using the finite element software SAP2000 v14, through a 3-D solid mesh. Water motion inside the tank is simulated using the mechanistic model proposed by Housner (1963). Results show that the tank's concrete structure raises lateral displacements caused by dynamic loads of wind as its water acts to reduce these displacements. Depth variation due to water consumption changes considerably the reservoir's damping characteristics, meaning that the water plus tank ensemble raises lateral displacement. Water supply tanks effects over dynamic behavior should not be neglected during the structural design of high buildings.*

Keywords: *Concrete buildings, Passive vibrations control, Wind-induced vibrations, Tuned liquid dampers*

1 INTRODUCTION

The intensive land occupation in urban centers is one of the main reasons behind the verticalization of structures in certain Brazilian cities. Constructing higher buildings is the solution utilized by builders and contractors to guarantee financial return of their investments.

Structures' dynamic behavior becomes a key factor in structural design of taller and slender buildings. Wind dynamic loads that were once neglected in modeling may induce horizontal displacements which are dangerous to the structure and to its occupants. Kareem (1983) lists some of the problems caused by lateral movement in buildings such as structural failure, cladding and partition damage. In addition to those, top floors occupants may experience motion sickness due to excessive acceleration.

In Brazil, most residential and office buildings have a water supply tank placed above last storey, whose volume is equivalent to at least the 24-hour water consumption of the occupants plus the firefighting system water reserve. This reservoir may affect the dynamic behavior of the main structure by either damping or intensifying lateral displacement, so it is important to verify the ensemble's mechanical behavior when subjected to wind loads.

In this paper, a 14-storey concrete residential building constructed in Fortaleza is modeled using a 3-D finite elements mesh through SAP2000 v14. Two different phenomena are verified: the influence of the empty reservoir over the main structure's normal modes and the changes in horizontal displacement of the top floor due to dynamic wind loads for different water tank depths, since liquid level varies during the day as a result of the occupants' water consumption.

2 BUILDING MODELING

2.1 Main structure

The studied building consists of a 14-storey concrete structure designed to house three apartments per floor. Ceiling height measures 2.88 m for all floors, except for the lowest level, where it measures 3.06 m. Ground-level pillars' bases are completely restrained in order to simulate a rigid ground-structure link. Underground parking facilities are not represented in this model since their robustness and the ground-structure interaction would restrict any underground lateral displacement.

Only the concrete infrastructure is considered in the analyses. Columns and beams are modeled according to the buildings' blueprints and slabs are substituted by diaphragm restraints. Slabs' loads are calculated and distributed to the beams. Concrete is considered as a uniform material with an elastic modulus E of 30.67 GPa, a Poisson's ratio ν of 0.2 and a specific weight γ of 24525 N/m^3. Structural viscosity is not considered. Figure 1 shows a perspective of the final model.

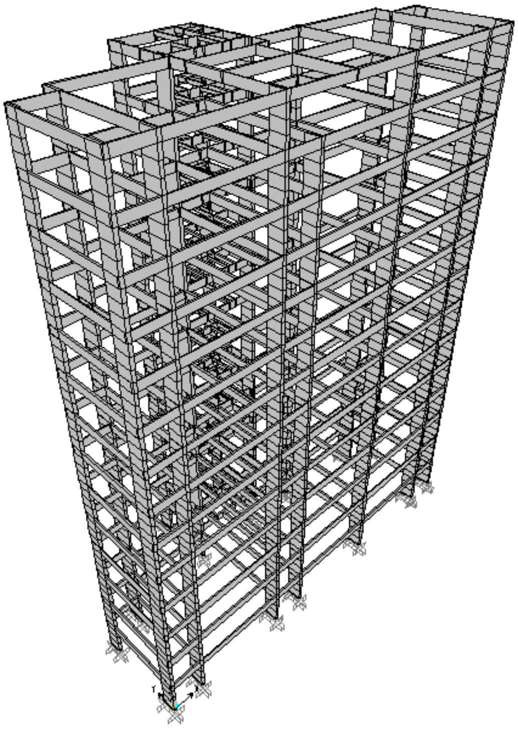

Figure 1. Concrete residential building

2.2 Water supply tank

The water supply reservoir structure consists of four concrete pillars supporting a 5.94 x 5.09 x 2.02 (m^3) concrete tank. An auxiliary slab is also constructed to support the mechanisms used for water pumping. Given that the analysis of the reservoir is not the main objective of this paper, the tank itself was not modeled. Instead the corresponding loads and a diaphragm constraint are applied to the four supporting columns. Figure 2 shows an overview of the tank's structure.

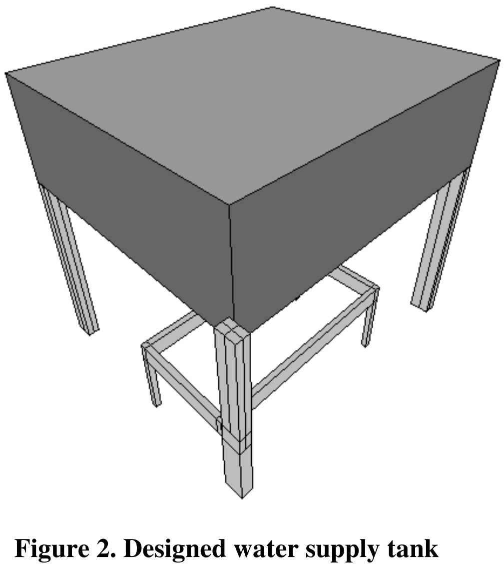

Figure 2. Designed water supply tank

2.3 Stored water

As the structure moves due to wind excitation, the stored water will be set in motion as well. Liquid movement is characterized by sloshing that has to be considered for an accurate analysis unless the tank is completely full (Housner, 1963; Chandrasekaran & Krishna, 1965).

Literature features plenty of mechanical models to simulate liquid sloshing behavior in tanks, varying from simple spring-mass systems (Graham & Rodriguez, 1951) to arrangements that consider the fluid's viscous behavior (Yu et al, 1999). Among these models, the one proposed by Housner (1963) was developed expressly to simulate elevated water tanks. It divides the liquid in two different portions: one that contributes to sloshing (m_1) and other that acts as part of the reservoir, following its movement (m_0). A spring of rigidity k_1 is associated to the sloshing mass, as presented in Fig. 3.

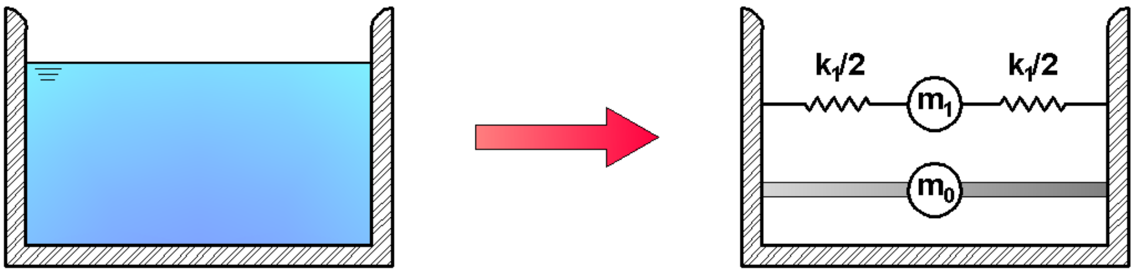

Figure 3. Housner's model

Both masses and the rigidity k_1 are determined by Eq. (1) to (3) (Epstein, 1974 cited by Livaoğlu, 2008, p. 134).

$$m_0 = 1.155 \ \frac{h}{L} \ \tanh\left(0.791 \ \frac{L}{h}\right) \ M \tag{1}$$

$$m_1 = 0.264 \ \frac{L}{h} \ \tanh\left(3.162 \ \frac{h}{L}\right) \ M \tag{2}$$

$$k_1 = 3.162 \ \frac{g}{h} \ \tanh\left(3.162 \ \frac{h}{L}\right) \ m_1 \tag{3}$$

where h is the water column depth, L is the tank's horizontal dimension in the direction of the lateral displacement, M is the stored water's mass and g is the gravitational constant.

Given that the reservoir walls are not represented in the model, m_0, m_1 and k_1 are equally divided amongst the tank's four supporting pillars. The sloshing mass and its spring are modeled in SAP 2000 as four loaded vertical frame elements with lateral rigidity equals to $k_1/4$.

It is important to observe that lateral displacements of the building will also move the stored water. Water in movement in a rigid container may act as a passive vibration control technique that dissipates energy through wave breaking and fluid's viscous behavior called Tuned Liquid Damper (Kareem & Sun, 1987).

This vibration control method was applied experimentally to the Nagasaki Airport Tower in 1987 and to two other high structures in Japan in 1987 and 1992 (Tamura et al, 1995).

Obtained results shows TLDs are efficient damping tools in those cases. Later, certain high buildings were conceived with TLDs to guarantee structural stability, such as the One King West Tower (Toronto, Canada) and the One Rincon Hill Tower (San Francisco, USA) (Morsy, 2010).

2.4 Wind dynamic loads

The calculus for dynamic wind load pressure intensity is regulated by the Brazilian code NBR 6123/88. It proposes a formulation that accounts for multiple physical factors, like the structure's form, the terrain's surface roughness and the building's height. In this study, the wind pressure distributed over the structure's outer wall was calculated and reduced to equivalent forces applied on each storey as lateral loads.

Looking for the worst possible scenario, wind loading was calculated and applied to the building in the direction of the structure's lowest lateral rigidity, since it would offer less resistance to lateral displacements in that direction.

Although the NBR 6123/88 code formulates how the wind intensity should be calculated, it does not comment on the time function that governs this loading. Rushes of wind may be described as a series of triangular functions (Rausch, 1933 cited by Blessmann, 1998, p.69). These triangular pulses have a period of one second, varying from maximum intensity to zero. The time span between two consecutive peaks is considered as three times the first natural period of the analyzed structure. Figure 4 illustrates de behavior of this triangular function.

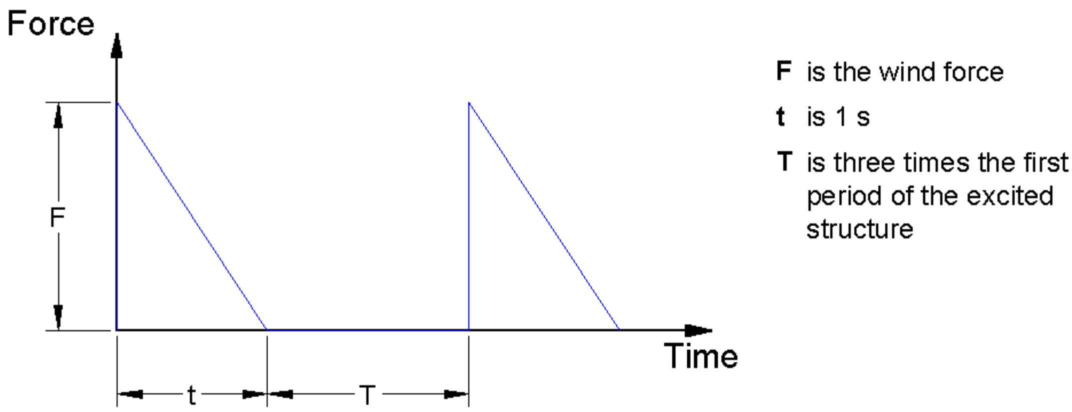

Figure 4. Wind load

3 CONCRETE RESERVOIR'S INFLUENCE OVER THE MAIN STRUCTURE

It is important to determinate how the concrete reservoir affects the main structure dynamic behavior since it may raise lateral displacement and/or acceleration. To do so, a modal analysis of the building with and without the empty reservoir was simulated, followed by a wind load analysis.

Modal analysis of the main structure reveals its ten first modes. Doing the same analysis to the structure/empty reservoir couple, it is possible to verify if known modes had a frequency change. Table 1 summarizes the results found in this simulation. The first three modes suffer a significant reduction in frequency, meaning that the structure becomes more susceptible to dynamic loads of lower frequencies.

Table 1. Main modal frequencies of the concrete building

Mode	Direction	Frequency (Hz)		Difference (%)*
		W/O Tank	With Tank	
1st Bending	y	1.239	1.176	-5,11%
1st Bending	x	1.906	1.605	-15.78%
1st Torsion	z	2.130	2.079	-2.40%
2nd Bending	y	3.730	3.757	0.73%
3rd Bending	y	6.300	6.300	0.01%
2nd Bending	x	6.412	6.436	0.38%
2nd Torsion	z	7.100	7.103	0.05%
4th Bending	y	8.840	8.821	-0.22%

* Difference relative to the W/O Tank case.

This change in frequency in this structure may be meaningless, since it is not very high, but in higher structures where first mode frequency is around 1 Hz, this type of reduction could be very dangerous, since wind resonance would become an issue.

Regarding the wind excitation, both structures are submitted to two dynamic pulses as the ones defined in the previous section. The displacement of the top floor ceiling were obtained and compared in Fig. 5. Both curves have similar behavior, but the structure with empty tank curve shows significantly higher peaks of displacement after the application of a second wind pulse, with a maximum difference of approximately 30% between peaks (0,283 mm).

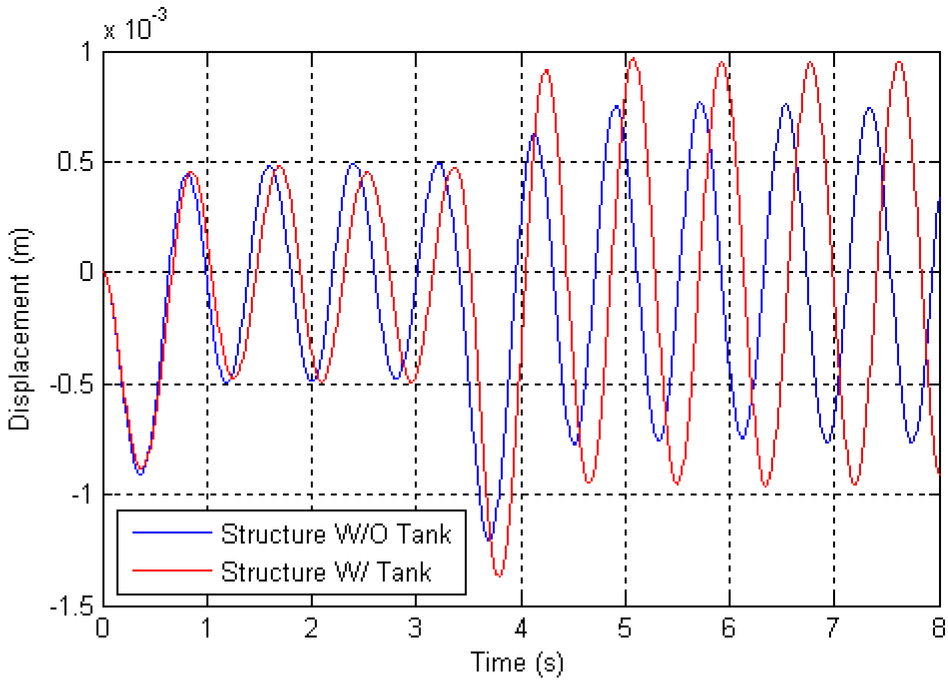

Figure 5. Comparison between horizontal displacements considering the effects of the empty tank

4 WATER DAMPING EFFECTS

Having verified the influence of a dry concrete reservoir over the main structure's dynamic behavior, it is now possible to analyze how liquid-structure interaction will act during wind loads. Since the occupants' water consumption varies during the day, five different water depths were used in the simulation, varying from 0.5 m (equivalent to the minimum volume for firefighting purpose, as determined by the Brazilian code NBR 5626/98 and by the Military Firefighters Corps) to 1.7 m, leaving a 30 cm gap between the reservoir's cover and water's free surface.

As in the previous section, the displacements on the ceiling of the highest storey in each case are compared. Table 2 contains the calculated parameters of Housner's model for each water depth. Wind's dynamic load is the same utilized in previous cases, and the comparison between horizontal displacements for each case can be seen in Fig. 6 to 8.

Table 2. Housner's model parameters for different water depths

h (m)	0.5	0.8	1.1	1.4	1.7
m_0 (kg)	1469.74	3762.47	7110.76	11494.75	16855.62
m_1 (kg)	12329.65	19053.00	24971.87	29979.43	34075.47
k_1 (N/m)	16743.70	39983.12	68683.40	98991.19	127889.10
Resonant Frequency (Hz)	0.19	0.23	0.26	0.29	0.31

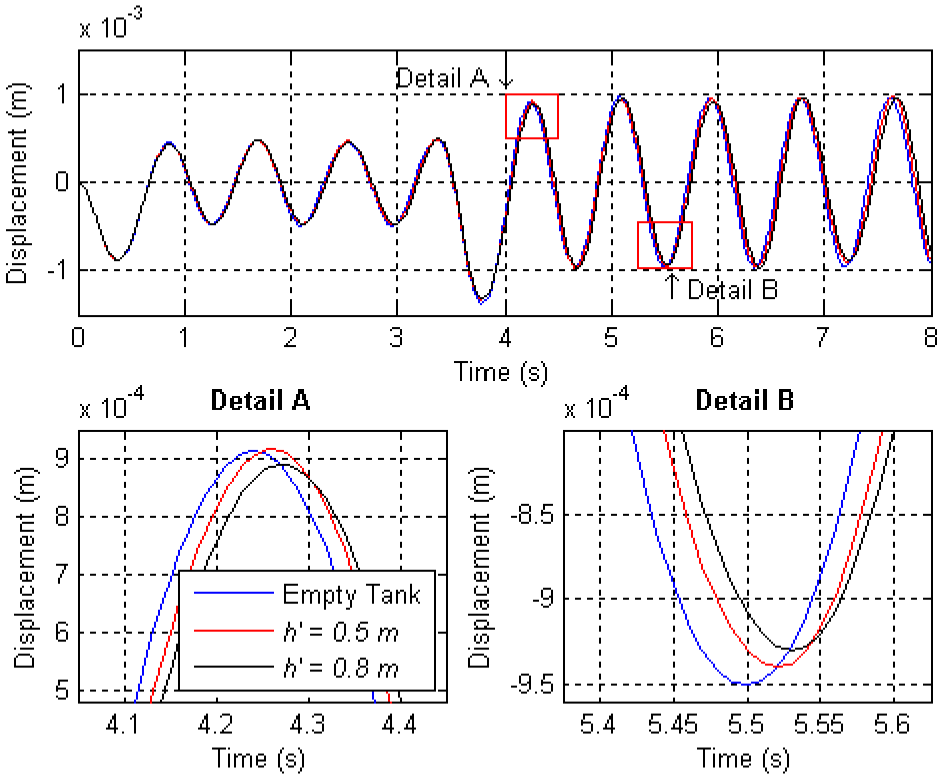

Figure 6. Displacement comparison: tank's water depths of 0.5 m and 0.8 m and the empty tank

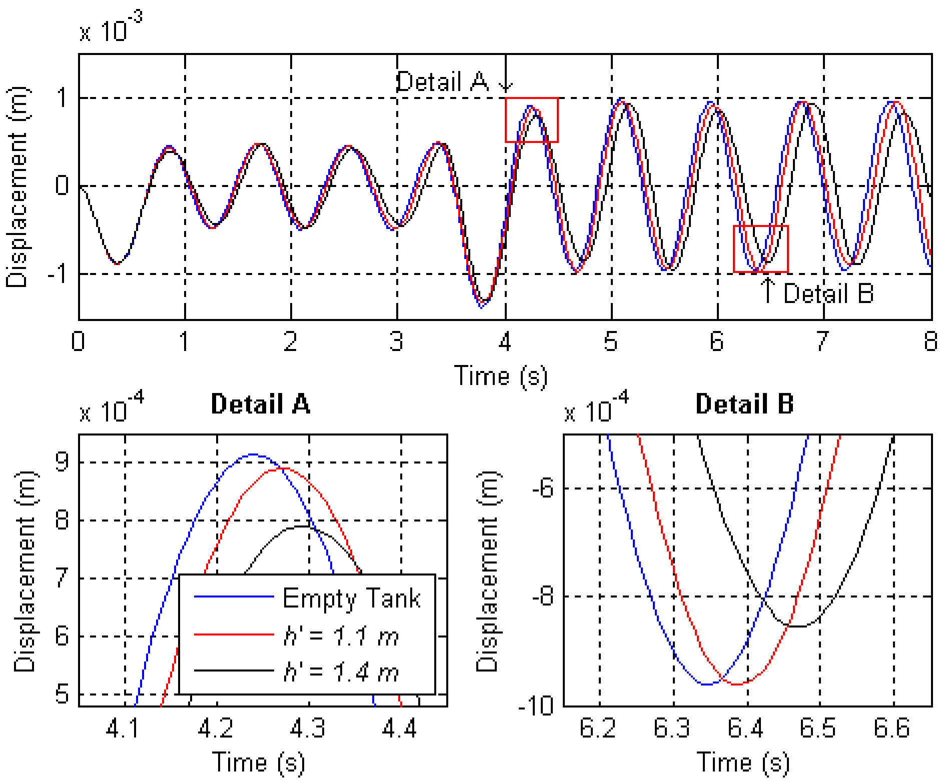

Figure 7. Displacement comparison: tank's water depths of 1.1 m and 1.4 m and the empty tank

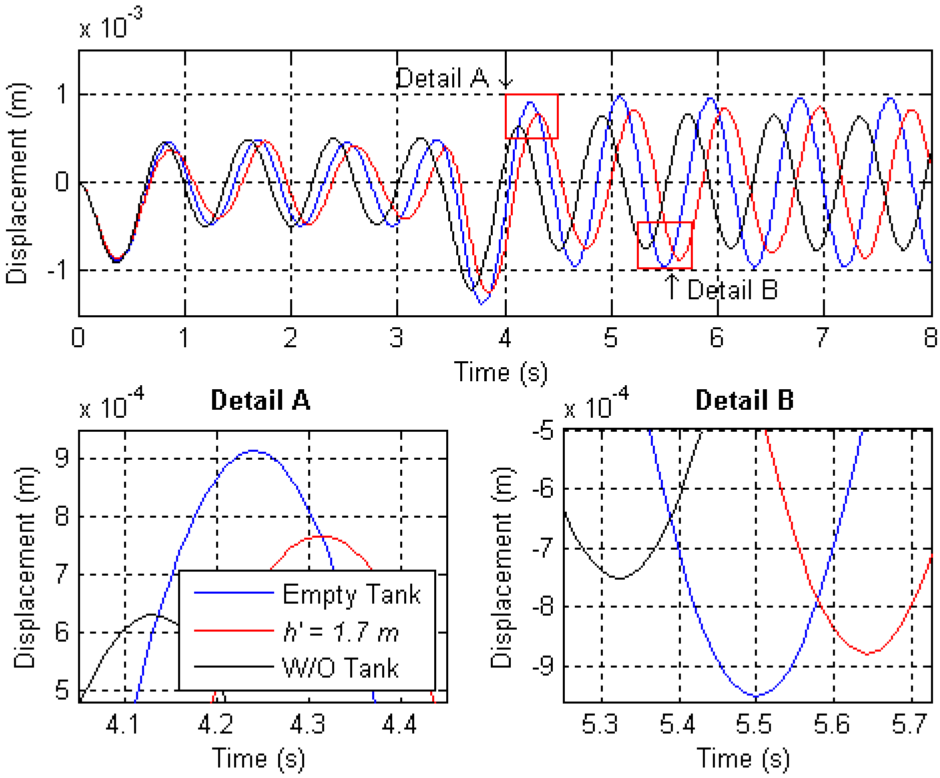

Figure 8. Displacement comparison: tank's water depth of 1.7 m, the empty tank and the main structure

Results show that the increment of stored water in the tank is followed by a raising damping effect, since displacement amplitude diminishes as the water column height rises. The reservoir acts as TLD.

Although this damping characteristic exists, TLD are fully functional when their frequencies match that of the target structure. The difference between the structure's and the water's normal frequencies (as noted in Tables 1 and 2) shows that the reservoir is not an optimized damping system.

The best damping response was observed at h = 1.7 m, where the lateral displacements obtained approach those of the main structure without water tank. It is important to note that the water in the reservoir causes a new frequency shift in the normal modes, as seen in Fig. 8, where peaks from the h = 1.7 m case do not coincide with peaks from the empty tank case. This means that the main normal mode frequencies where once again reduced.

5 CONCLUSION

A water supply tank may considerably impact the dynamic behavior of a concrete building. The reservoir's influence over the structure's main vibration modes may lead to unwanted resonant frequencies, resulting in the increase of lateral displacement of the structure. Despite its size and mass, this kind of elevated reservoir should not be neglected during the design of wind- susceptible buildings.

The damping characteristics of the water stored in the container show that it has potential to mitigate lateral displacements. Even so, it could only suppress the excessive displacement caused by the tank's concrete structure when it was on its maximum capacity, a condition that can't be always guaranteed since water consumption varies during the day.

It is possible to improve the functioning of the reservoir as a TLD, so that its damping capacity would actually guarantee structural stability. Existing water supply tanks may be modified to achieve optimal damping parameters, as reported by Kareem et al (1999) and Morsy (2010). The introduction of solid particles that dissipate energy through collision (Tamura et al, 1995), the installation of baffles and a new configuration of internal sections are some of the actions that could actually turn the tank into an effective TLD.

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