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EFFECTS OF AFTERSHOCKS ON THE BEHAVIOR AND STRUCTURAL INTEGRITY OF WATER TANKS

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ABSTRACT

This paper examines the effects of aftershocks on the behavior and structural integrity of water tanks. To be sure, there are many research works that investigated the influence of multiple earthquakes on the response of single-degree-of-freedom systems or 2-D and 3-D multi-degree-of-freedom framed structures. On the other hand, the investigation of seismic response of tanks is limited to single ground motions, e.g., using the 'design' earthquake. This study investigates the inelastic response of concrete tanks subjected to seismic sequences, a phenomenon which has not been investigated in the past. Real seismic sequences are examined, where the former have been recorded during a short period of time (up to three days), by the same station, in the same direction, and almost at the same fault distance. It is concluded that due to aftershocks effect, it seems to be defective to take into account only single earthquake records in tanks design process.

Keywords: Aftershocks; concrete water tanks; inelastic behavior; repeated earthquakes; structural integrity

1. INTRODUCTION

Heavy damage or even collapse of concrete tanks during intense seismic ground motions have been mentioned and acknowledged in the past, e.g., during Long Beach earthquake (1933), Niigata earthquake (1964), Alaska earthquake (1964), San Fernando earthquake (1971), Maule earthquake (2010), amongst others. These failures have lead to direct loss of tanks' structural integrity as well as to indirect catastrophe such as fires, environmental pollution, etc. It is evident that the reliable seismic design of tanks subjected to intense earthquakes is a vital topic for structural engineering. For this reason, numerous modern seismic codes examined the seismic design of tanks such as AWWA (2005), API 650 (2005), Eurocode 8 (2005) and FEMA-750 (2009). Furthermore, many research studies have been published that examined the behavior of tanks under strong earthquakes, such as Jacobsen (1949), Graham and Rodriguez (1951), Housner (1957, 1963), Veletsos [1974, 1987, 1990], Haroun and Housner (1979, 1981, 1982), Malhotra (1997a,b, 1998) and Minoglou et al. (2013), amongst others. All these studies or standards ignoring the response of tanks subjected to repeated earthquakes, i.e. ignoring the impact of aftershocks on tanks' behavior and capacity. It should be mentioned that influence of aftershocks on structural response of SDOF systems and 2-D or 3-D building structures has been considered in detail, e.g., in works of Hatzigeorgiou (2010a,b), Hatzigeorgiou and Beskos (2009), Hatzigeorgiou and Liolios (2010), Loulelis et al. (2012), Faisal et al. (2013), Hatzivassileiou and Hatzigeorgiou (2015). The only one work that examined the influence of repeated earthquakes on tanks is that of Konstandakopoulou and Hatzigeorgiou (2017a) but it has exclusively to do with steel tanks and not with concrete ones. Thus, the need to propose an effective method for the inelastic analysis of concrete tanks, taking also into account the influence of aftershocks is obvious. This paper examines the behavior of concrete tanks under the action of repeated earthquakes to cover the abovementioned gap, giving useful conclusions and findings.

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2. MODELLING OF LIQUID STORAGE CONCRETE TANKS UNDER SEISMIC LOADS

The response of liquid storage concrete tanks under static and dynamic loads, such as hydrostatic and hydro-seismic pressure, has been examined in-detail in the past, e.g., one can consult Jaiswal et al. (2004) and Konstandakopoulou and Hatzigeorgiou (2017b). A simplified model is adopted here using the RUAUMOKO finite element dynamic analysis program (Carr, 2008) to represent an elevated water square tank . The structure under consideration is assumed to be completely filled with water. The present of fluid for the evaluation of seismic response is considered by the added mass technique. The tank structure under consideration is shown in Fig. 1.

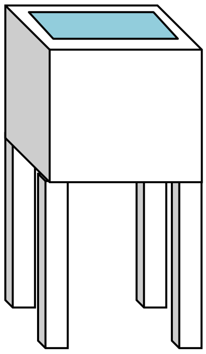

Figure 1: Elevated water concrete tank

The simplified model of the tank is shown in Fig. 2, which is based on Jaiswal et al. (2004)

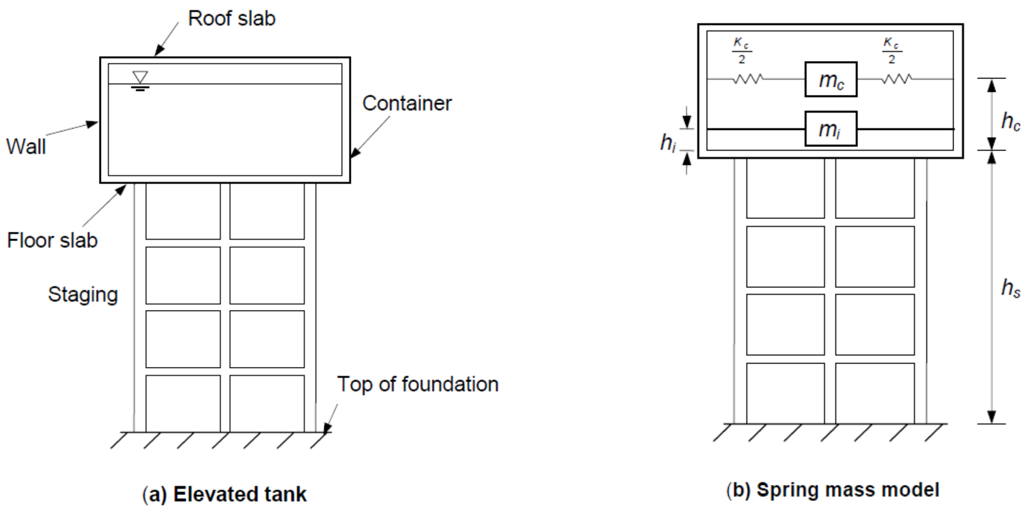

Figure 2: Simulation of elevated water concrete tank (adopted from Jaiswal et al., 2004)

In order to evaluate reliably the seismic behavior of elevated concrete tanks, a simplified model consists of three-dimensional beam-column elements is used. The structural design of the tank follows the European Standards, i.e., using Eurocodes 1, 2 and 8. The foundation and the soil below the elevated tank are assumed to be rigid, i.e., ignoring the soil-structure interaction phenomenon.

The elevated tank consists of beam–column members and it is located in a high-seismicity region of Europe considering both gravity and seismic loads where a design / peak ground acceleration (PGA) of 0.30g and soil class C according to EC8 are assumed. The tank has been designed for the following loading combinations:

a) 1.35G+1.50Q

b) 1.00G+ψQ+1.00E

where G, Q and E correspond to dead, live and earthquake loads, respectively, and ψ is the combination coefficient for live load, assumed to be ψ=1.00 in this study. Furthermore, the total vertical loads (self-weight and water-weight) is equal to 1088 kN, which is which is received by the four RC columns (see Fig. 1). Material properties are assumed to be 30 MPa for the concrete compressive strength (concrete grade C30) and 500 MPa for the yield strength of both longitudinal and transverse reinforcements (steel grade B500c). All columns have square section with side 50 cm, total length 10.0m and the selected longitudinal reinforcement amount (number of bars and diameters in mm) and arrangement as shown in Fig3. This figure also demonstrates the bending moment - axial force interaction diagrams for columns, considering 2-D and 3-D response.

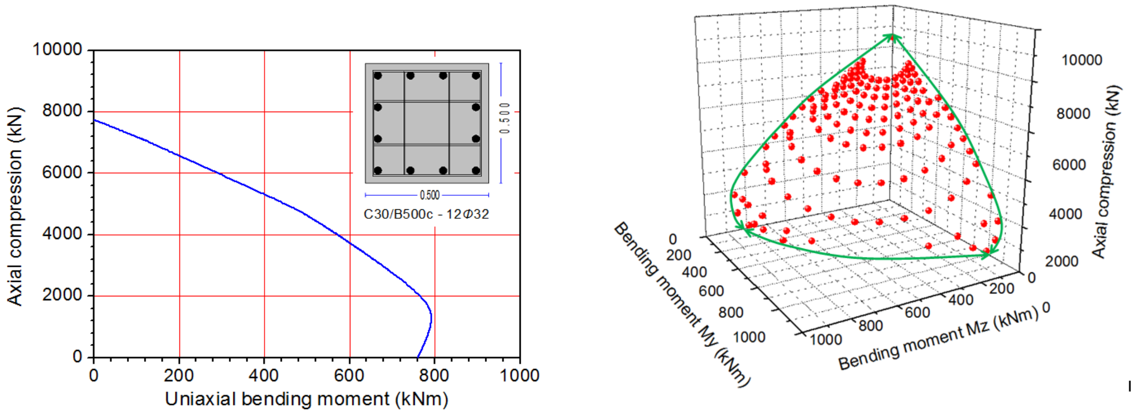

Figure 3: Bending moment - axial force interaction diagrams for columns

An inelastic structural Multi-Degree of Freedom (MDOF) system with viscously damped force-deformation relationship is used to investigate the structural response for actual records. The dynamic equilibrium equation of these systems is given in incremental form

$$M\ddot{u} + C\dot{u} + K^{T}u = -Ma_{g} \qquad (1)$$

where M is the mass matrix, u the relative displacement vector, C the viscous damping matrix, K^T the tangent (inelastic) stiffness matrix, the acceleration vector of the ground motion and the upper dots stand for time derivatives. The solution of the equation of motion has been performed using the Ruaumoko program (Carr 2008).

3. REPEATED EARTHQUAKES

This paper examines strong ground motions correspond to real seismic sequences, which have been recorded during a short period of time (up to three days), by the same station, in the same direction, and almost at the same fault distance. These seismic sequences are namely: Chalfant Valley (July 1986 - 2 events), Coalinga (July 1983 - 2 events), Imperial Valley (October 1979 - 2 events) and Whittier Narrows (October 1987 - 2 events) earthquakes. The complete triplets (2-horizontal and 1-vertical components) of these earthquakes were downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center (2017) and appear in Table 1.

Table 1. Seismic input data

No.	Seismic sequence	Station	Date (Time)	Magnitude (M_L)
1	Chalfant Valley	54428 Zack Brothers Ranch	1986/07/20 (14:29) 1986/07/21 (14:42)	5.9 6.3
2	Coalinga	46T04 CHP	1983/07/22 (02:39) 1983/07/25 (22:31)	6.0 5.3
3	Imperial Valley	5055 Holtville P.O.	1979/10/15 (23:16) 1979/10/15 (23:19)	6.6 5.2
4	Whittier Narrows	24401 San Marino	1987/10/01 (14:42) 1987/10/04 (10:59)	5.9 5.3

For the most of civil structures, between two consecutive seismic events a time gap equal to 20~30 sec is adequate to cease their oscillation due to damping. Therefore, the real time gap, which can be equal to days or weeks (i.e., thousands or millions of seconds), can be substituted by the aforementioned time gap. However, especially for the evaluation of seismic behavior of tanks, a time gap equal to 30 sec is not enough, considering that for the fluid motion (e.g., sloshing) the corresponding damping ratio is rather small, about 0.5%. For this reason, in this study, the time gap between two consecutive seismic events is set equal to 180 s (=3.0 minutes).

4. SELECTED RESULTS

Selected characteristic results, that describe the inelastic behavior of the examined elevated RC tanks under the action of the aforesaid four real seismic sequences, are provided in this section. For example, Fig. 4 shows the time history of horizontal displacement for the bottom of concrete tank (or for the top of reinforced concrete columns), examining the Whittier Narrows earthquakes. For comparison reasons, the response for both single (individual) records and seismic sequence is shown. It is obvious that repeated earthquakes lead to different seismic response for reinforced concrete tanks in comparison with the corresponding single earthquakes.

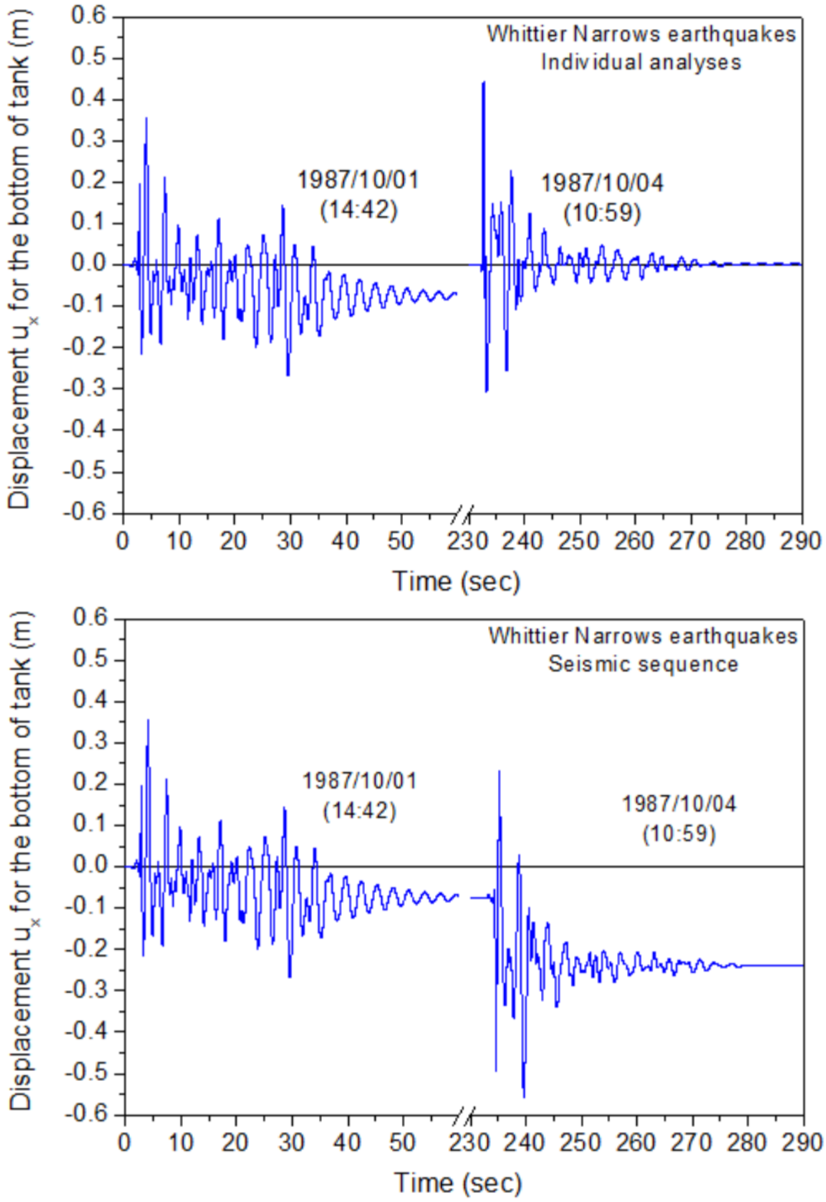

Figure 4. Horizontal displacement of the bottom of tank - Whittier Narrows earthquakes (1987)

According to previous studies examined reinforced concrete structures under repeated earthquakes, e.g., Hatzigeorgiou and Liolios 2010, Hatzivassileiou and Hatzigeorgiou 2015, the most critical parameter that is affected by aftershocks is the structural damage. For this reason, this study mainly focuses on local and global damage indices, i.e., damage indices according to Park and Ang (1985), Banon and Veneziano (1982), Cosenza et al. (1993) approaches.

More specifically, Park and Ang (1985) damage index, DI_{PA}, can be expressed by

$$DI_{PA} = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h \tag{2}$$

where δ_m is the maximum deformation of the element, δ_u is the ultimate deformation, β is a model constant parameter (usually, β=0.05~0.20) to control strength deterioration, $\int dE_h$ is the hysteretic energy absorbed by the element during the earthquake, and P_y is the yield strength of the element. In this work, parameter β is set equal to 0.20, as suggested by Hatzigeorgiou and Liolios (2010).

Banon and Veneziano (1982) damage index, DI_{BV}, can be expressed by

$$DI_{BV} = \frac{\sqrt{\left(\frac{\mu_m}{\mu_y} - 1\right)^2 + \left(1.1\left(\frac{2E_h}{P_y \mu_y}\right)^{0.38}\right)^2}}{\text{The numerator for monotonic loading}} \tag{3}$$

where μ corresponds to the ductility.

Finally, according to Cosenza et al. (1993), the ductility damage index, DI_D, can be defined as

$$DI_D = \frac{\mu_m - 1}{\mu_u - 1} \tag{4}$$

Furthermore, this study also examines the behavior of elevated reinforced concrete tanks for different values of earthquake incident angle, a phenomenon that has received little attention in the past (Konstandakopoulou and Hatzigeorgiou, 2017b). Figures 5-7 depict the aforesaid damage indices.

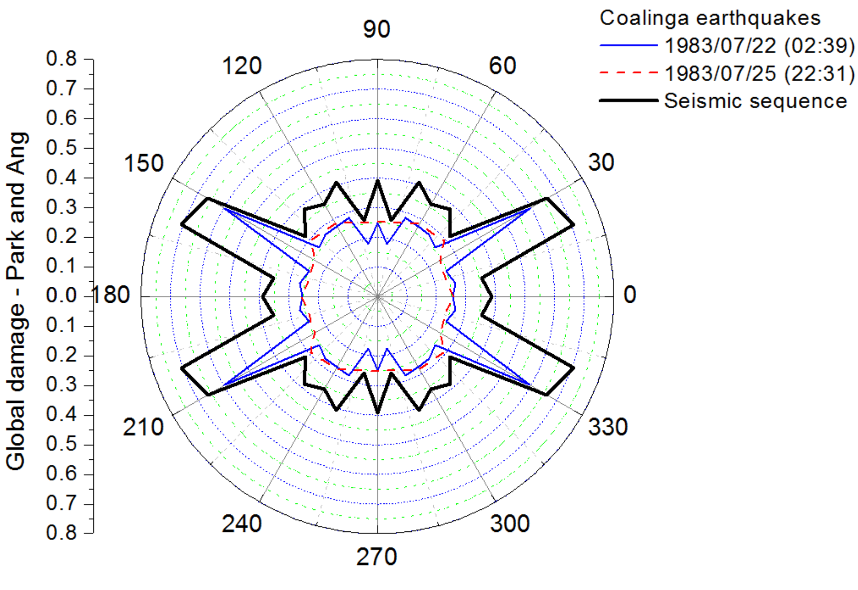

Figure 5. Park-Ang (1985) damage index for various incident angles

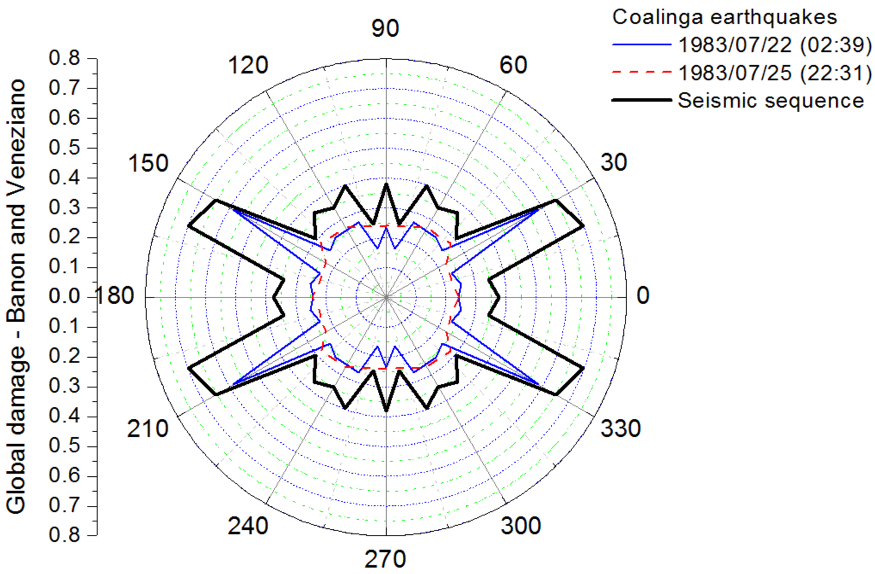

Figure 6. Banon-Veneziano (1982) damage index for various incident angles

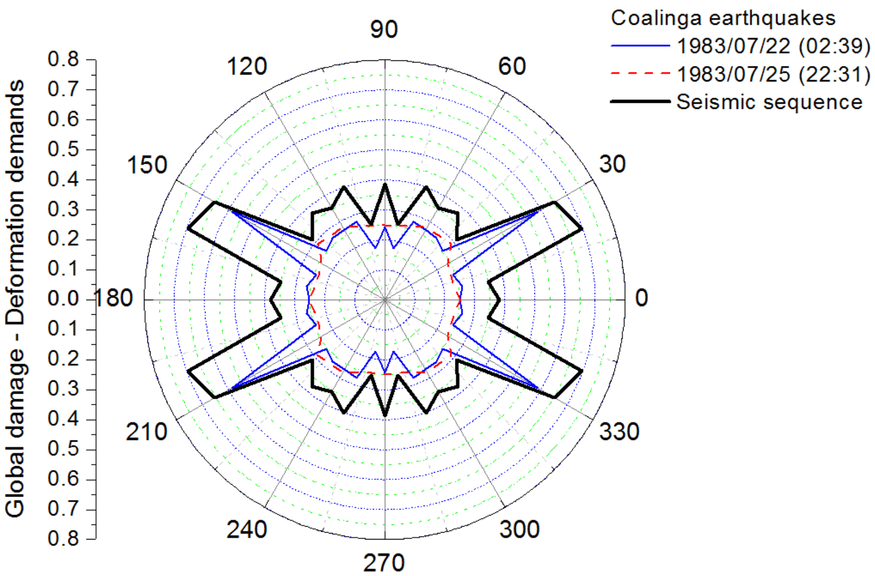

Figure 7. Cosenza et al. (1993) damage index for various incident angles

5. CONCLUSIONS

In this research study, the dynamic inelastic response of elevated reinforced concrete tanks under repeated earthquakes is investigated. The main contribution of this work has to do with the quantification of the aftershocks' effect into the seismic response of reinforced concrete tanks, a phenomenon which had not been studied in the past. This paper examined real repeated earthquakes. Detailed examination of the response of concrete tanks makes clear that aftershocks strongly affect their seismic response as well as their structural integrity, at least at the framed structure that support the tank, e.g., reinforced concrete columns. For these reasons, the pertinent provisions of seismic codes that have to do with the design of liquid storage tanks should be reinstated since, at the moment, the seismic design of these special structures is exclusively prescribed by the idealized and individual 'design earthquake'.

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