STEEL WATER AND WASTEWATER TANKS SUBJECTED TO MULTIPLE EARTHQUAKES

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1. ABSTRACT

The inelastic response of water and wastewater steel tanks under multiple earthquakes is investigated in this paper. The proposed study focuses on the quantification of the seismic sequence effect into steel tanks, a phenomenon which has inadequately studied in the past. This study takes into account real seismic sequences that have been recorded during a short period of time, i.e., up to three days. In these cases, the multiplicity of earthquakes can lead to important damage accumulation while, due to lack of time, any rehabilitation action between consecutive ground motions is impractical. It is concluded that multiple earthquakes should be taken into account while it seems to be unreliable to consider only single earthquake records in steel tank design process which leads to underestimated demands in terms of bearing capacity and deformation.

2. INTRODUCTION

Steel tanks are important civil structures that are extensively used worldwide in urban resource water, petroleum industry and nuclear power plants. These constructions consist of a steel thin wall that resists internal liquid pressure and a thin roof steel plate. Failures of steel tanks during strong ground motions have been recorded in the past and had severe consequences, e.g., 1964 Alaska earthquake, 1971 San Fernando earthquake and 2013 Marlborough (New Zealand) earthquake. The damage of liquid storage steel tanks will not only lead to large direct loss, but also produces serious secondary catastrophe such as environmental pollution, fire and/or nuclear radiation. Thus, the reliable assessment of behaviour and capacity of steel tanks subjected to severe seismic events is a very important engineering topic [1].

Modern seismic codes examine the seismic design of tanks such as API 650 [2], Eurocode 8 [3] and FEMA-750 guidelines [4]. Furthermore, one can mention here the pioneering work of Veletsos [5] and of Haroun and Housner [6], where reliable and effective analysis and design methods were proposed. Additionally, Minoglou et al. [1], examined the optimal design of cylindrical thin-walled steel tanks under seismic loads. The aforementioned proposed methods or codes provisions have exclusively focused on the 'design' earthquake. Therefore, these studies or codes are insufficient for evaluating the seismic response of steel tanks under multiple earthquakes phenomena. It should be noted that, although the problem of multiple earthquakes has been acknowledged for civil structures, the pertinent studies have been exclusively proposed for SDOF systems [7-9] and 2-D or 3-D building structures [10-12]. Thus, there is not any research study investigated the behavior of steel tanks under multiple earthquake phenomena and the need for the development of an efficient methodology for the inelastic analysis of liquid storage tanks under sequential ground motions is obvious. This study focuses on the behavior and capacity of water and waste water of steel tanks under multiple earthquakes to cover the aforementioned gap.

3. DESCRIPTION OF STRUCTURES, MODELING AND EARTHQUAKE DATA

Figure 1 demonstrates an elevated cylindrical steel water tank with above-ground tank height, ht, external radius R, thickness s, total height h, and fluid level H. Tanks can be characterized as 'tall' (H/R>1) or 'broad' (H/R≤1) [13].

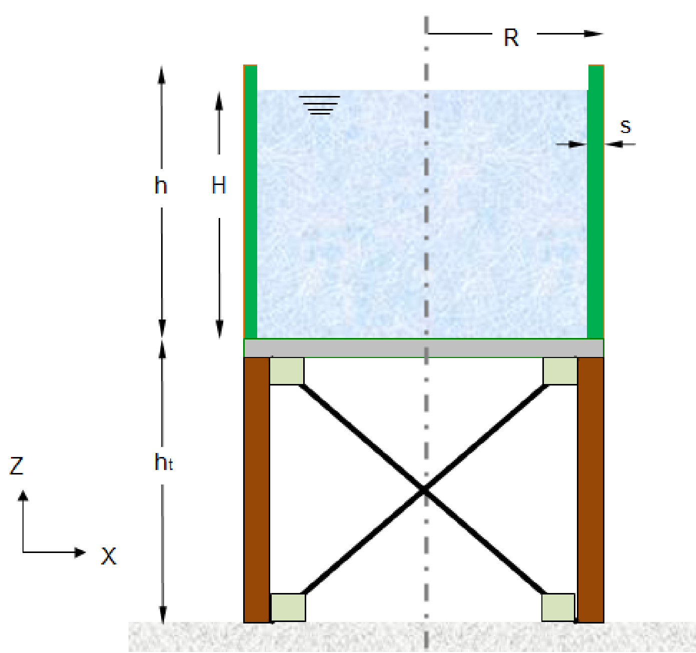

Fig. 1: Elevated steel water tank

Two elevated steel tanks are investigated here. The data of the examined tanks are presented in Table 1, where the parameters of geometry have been defined in Fig. 1. It should be mentioned that in any case, the thickness of the shell, *s*, varies between 10mm (top of the tank) to 20mm (bottom of the tank) where an averaged thickness of shell, $s_{av.}$=15mm is assumed.

Tank	R(m)	H(m)	H/R	$s_{av.}$ (mm)	$R/s_{av.}$	h_t(m)
1	3.0	6.0	2.00	15	200	6.0
2	3.0	2.0	0.67	15	200	6.0

Table 1: Geometry

The material of structure is steel with elasticity modulus E=200GPa, mass density ρ_s=7850kg/m^3 and yield stress, f_y=235MPa. The base of each elevated tank under consideration (at height h_t) is assumed to be rigid. The elevated structure is supported by six steel circular tubes with the aforementioned material parameters and the section parameters for these steel tubes are: diameter d_c=300mm and t_c=10mm (Ø300/10).

The vertical steel members (columns) can be appropriately modelled using various hysteretic models and in this study, the Al-Bermani bounding surface hysteresis model [14] is adopted. Furthermore, there are steel tubes with circular sections that have been used as braces connecting the aforementioned columns between themselves which have diameter d_c=150mm and t_c=5mm (Ø150/5). These diagonal steel members have complex behaviour, mainly due to instability phenomena and quite different response between tension and compression and in this study, the Remennikov hysteresis model [15] is adopted. The seismic inelastic response of the tanks is carried out using RUAUMOKO-3D analysis program [16]. The aforementioned hysteretic models of Al-Bermani and Remennikov, for columns and braces, respectively, are available in RUAUMOKO-3D and the typical force-displacement cyclic behaviour for these models appears in Fig. 2.

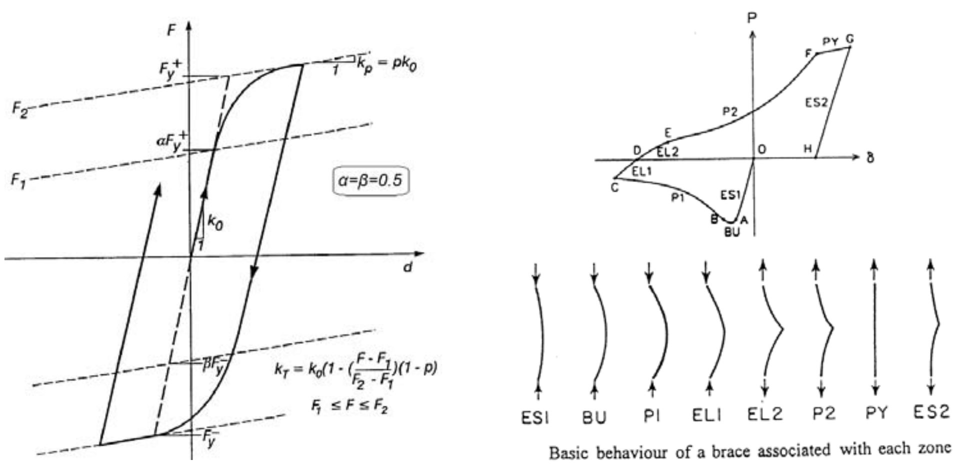

Fig. 1: Modelling of force-displacement cyclic behaviour: a) columns, b) braces [16]

Two 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 are examined in the following. These seismic sequences are namely: Coalinga

(July 1983 - 2 events) and Whittier Narrows (October 1987 - 2 events) earthquakes. Therefore, six earthquakes are taken into account, i.e., four individual seismic events and two seismic sequences. In any case, three components of each earthquake are used, i.e., in longitudinal, transverse and vertical direction.

4. RESULTS

The seismic inelastic behaviour of elevated steel tanks, which are subjected to the aforesaid real and artificial seismic sequences, is investigated here. Due to lack of space, selected results are provided here. This section focuses on the time history of horizontal displacements for the steel tank. Furthermore, the time history of sloshing of water surface is also examined. Thus, Fig. 3 presents the time history of horizontal displacement of the bottom of elevated tall tank for Coalinga earthquakes (1983). It is evident that the seismic response of tank is different for sequence and for single/individual ground motions.

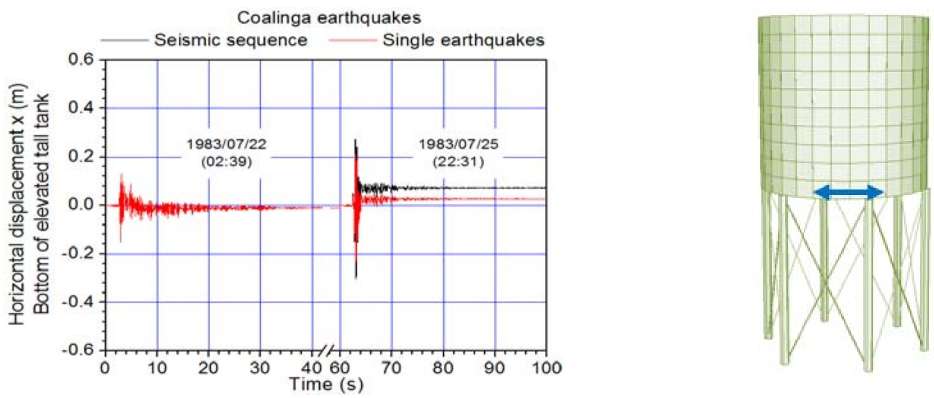

Fig. 3: Horizontal displacement of the bottom of tall tank - Coalinga earthquakes (1983)

In addition, Fig. 4 depicts the sloshing response of water for Coalinga earthquakes (1983). It is found that the oscillation of water surface differs between the cases of 'as-recorded' seismic sequence and of single (discrete and individual) earthquakes. The sloshing response is computed using the approach of Ref. [17]

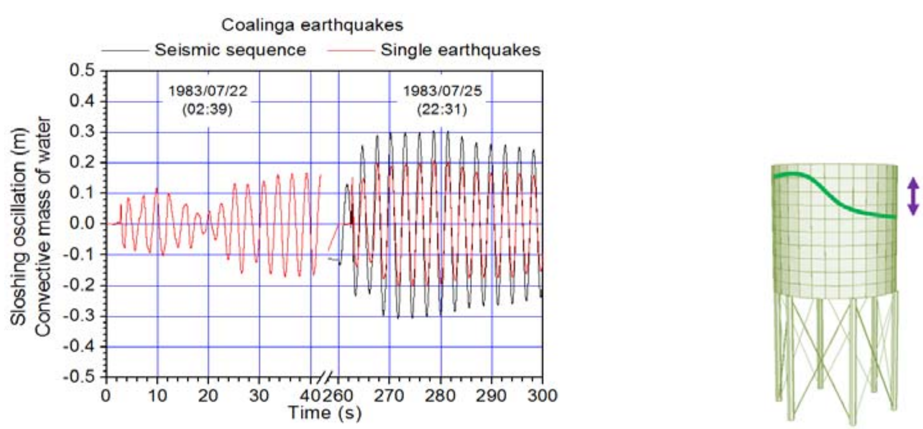

Fig. 4: Vertical sloshing of water - Coalinga earthquakes (1983)

The time history of horizontal displacement of the bottom of elevated broad tank, for Whittier Narrows earthquakes (1987), is provided in Fig. 5, for both case of 'as-recorded' seismic sequence and case of individual earthquakes. For the first earthquake, the seismic responses for both of these cases are identical, as expected. On the other hand, it is obvious from Fig. 9 that the seismic inelastic response of tank during the second earthquake is different between the aforementioned cases. The vertical oscillation of the water surface, i.e., its sloshing response, for Whittier Narrows earthquakes (1987), is shown in Fig. 6, both for single earthquakes and seismic sequence. It is obvious (as expected) that convective mass of water response appears to have quite higher period of oscillation (Fig. 6) in comparison with the oscillation of steel tank (Fig. 5). Furthermore, the oscillation of the convective mass of water differs between the cases of 'as-recorded' seismic sequence and of individual earthquakes.

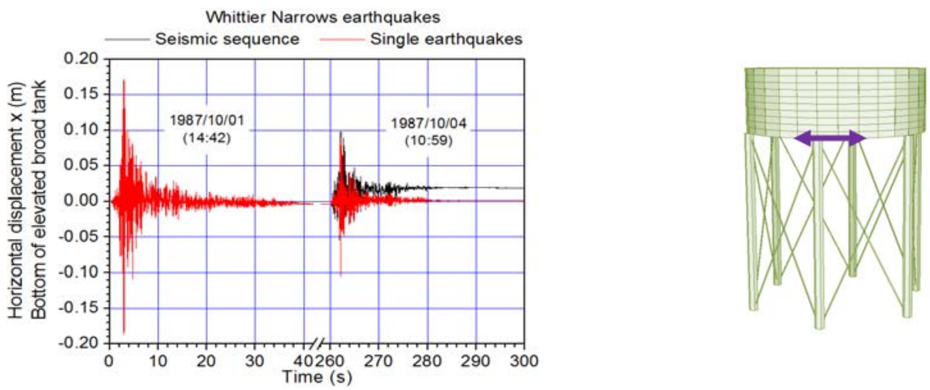

Fig. 5: Horizontal displacement of the bottom of tank-Whittier Narrows earthquakes (1987)

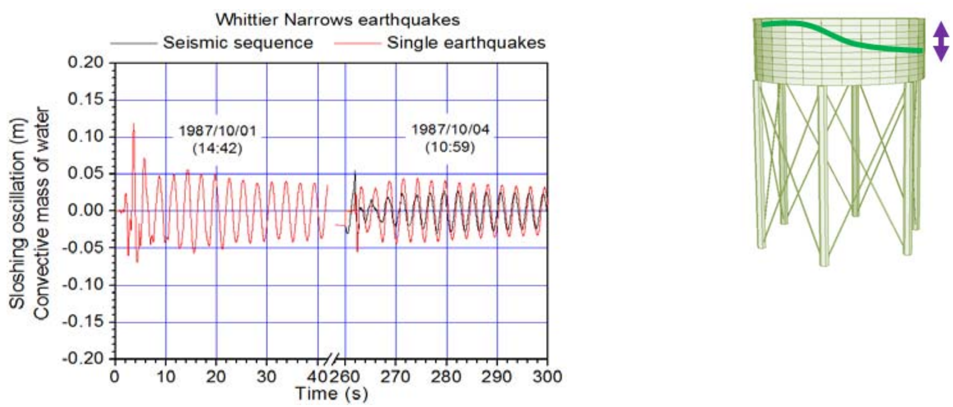

Fig. 6: Vertical sloshing of water - Whittier Narrows earthquakes (1987)

5. CONCLUSIONS

This paper investigated the dynamic inelastic response of steel tanks under multiple earthquakes. The main innovation of this work has to do with the quantification of the seismic sequence effect into steel tanks, a phenomenon which had not been studied in the past. Due to the lack of enough real seismic sequences records, this paper examined both real and artificial repeated earthquakes, where the latter have been generated by a rational and random combination of real single events. Detailed examination of the response of each tank makes clear that the multiplicity of earthquakes strongly affects its seismic response, not only for the structure itself but also for the dynamic response of fluid medium, e.g. sloshing. For this reason, the principles of performance-based seismic design should be reinstated since, at the moment, the seismic design of tanks is exclusively prescribed by the idealized and individual 'design earthquake'.

6. REFERENCES

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ΔΕΞΑΜΕΝΕΣ ΑΠΟ ΧΑΛΥΒΑ ΓΙΑ ΤΗΝ ΑΠΟΘΗΚΕΥΣΗ ΝΕΡΟΥ ΚΑΙ ΑΠΟΒΛΗΤΩΝ ΥΠΟ ΤΗ ΔΡΑΣΗ ΠΟΛΛΑΠΛΩΝ ΣΕΙΣΜΩΝ

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ΠΕΡΙΛΗΨΗ

Η ανελαστική απόκριση των δεξαμενών από χάλυβα για την αποθήκευση νερού και λυμάτων υπό τη δράση πολλαπλών σεισμών διερευνάται στην εργασία αυτή. Η προτεινόμενη έρευνα επικεντρώνεται στην ποσοτικοποίηση της επίδρασης σεισμικής αλληλουχίας σε δεξαμενές από χάλυβα, ένα φαινόμενο που δεν έχει μελετηθεί επαρκώς στο παρελθόν. Η εργασία αυτή λαμβάνει υπόψη πραγματικές σεισμικές αλληλουχίες που έχουν καταγραφεί σε σύντομο χρονικό διάστημα, δηλ. έως και τρεις ημέρες. Σε αυτές τις περιπτώσεις, η πολλαπλότητα των σεισμών μπορεί να οδηγήσει σε σημαντική συσσώρευση βλάβης, ενώ, λόγω έλλειψης χρόνου, οποιαδήποτε ενέργεια αποκατάστασης μεταξύ διαδοχικών εδαφικών κινήσεων εδάφους μοιάζει ανέφικτη. Με την παρούσα εργασία απορρέει το συμπέρασμα πως πρέπει να ληφθεί υπόψη η πολλαπλότητα των σεισμών, ενώ φαίνεται ανεπαρκές να λαμβάνονται υπόψη μόνο οι μεμονωμένοι σεισμοί στη διαδικασία σχεδιασμού δεξαμενών χάλυβα αφού τότε προκύπτουν υποτιμημένες απαιτήσεις όσον αφορά τη φέρουσα ικανότητα και την παραμόρφωση.