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Water and wastewater steel tanks under multiple earthquakes

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ABSTRACT

This study focuses on the inelastic response of water and wastewater steel tanks under multiple earthquakes. The main innovation of the proposed study has to do with the quantification of the seismic sequence effect into steel tanks, a phenomenon which has not been studied in the past. Firstly, this paper considers real seismic sequences that 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. In these cases, due to lack of time, any rehabilitation action is difficult or impractical and the multiplicity of earthquakes can lead to important damage accumulation. Furthermore, artificial seismic sequences are also examined where they have been generated by a rational and random combination of real single events. It is found that due to the multiple earthquakes effect, it seems to be unreliable to consider only single earthquake records in steel tank design process, since this long-established assumption leads to underestimated demands in terms of bearing capacity and deformation.

1. Introduction

Steel tanks are very important structures of lifeline, which are extensively used worldwide in urban resource water, petroleum industry and nuclear power plants. They 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., during the 1933 Long Beach earthquake, 1964 Niigata (Japan) earthquake, 1964 Alaska earthquake, 1971 San Fernando earthquake, 1979 Imperial Valley earthquake, 1989 Loma Prieta earthquake, 2003 San-Simeon earthquake, 2010 Maule (Chile) earthquake, and the 2013 Marlborough (New Zealand) earthquake. The damage or collapse 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. Therefore, the reliable assessment of behaviour and capacity of steel tanks subjected to severe seismic events is a very important engineering topic.

There are many modern codes that reliably examined the seismic design of tanks such as AWWA 2005 [2], API 650 [3], Eurocode 8 [4] and FEMA-750 guidelines [5]. Furthermore, many works have been proposed for the seismic design and analysis of steel tanks where numerous researchers have investigated the seismic behaviour and capacity of steel tanks theoretically, numerically and experimentally. It is well-known that the experimental seismic tests, due to their high cost and limited conditions, are not preferred. On the other hand, nonlinear analysis, both static (e.g., pushover) or dynamic (e.g. nonlinear time history analysis) is extensively adopted by engineers and researchers to evaluate reliably and inexpensively the behaviour and capacity of thin-walled steel tanks [1].

Early works of the dynamic response of tanks assumed rigid behaviour for tank and mainly examined the dynamic response of the contained fluid, e.g., see the works of Jacobsen [6], Graham and Rodriguez [7] and Housner [8,9].

It should be noted that the development of digital computers as well as of numerical methods have considerably improved the assessment of behaviour of tanks subjected to seismic loads. One can mention here the first application of computerized seismic analysis for liquid storage tanks by Edwards [10]. Then, various studies examined numerically the seismic behaviour of tanks. One can mention here the pioneering works of Veletsos [11–13] and of Haroun and Housner [14–16], where reliable and effective analysis and design methods were proposed. Furthermore, Minoglou et al. [1], examined the optimal design of cylindrical thin-walled steel tanks under seismic loads. Finally, Kim and Lee [17] and Malhotra [18–20] investigated the seismic performance of tanks with a variety of energy dissipation and isolation devices.

All 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.

Despite the fact that the problem of multiple earthquakes has been acknowledged for civil structures, the pertinent studies have been exclusively proposed for SDOF systems [21–24] and 2-D or 3-D building

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structures [25–30]. To the best of the authors' knowledge, there is not any research study investigated the behaviour 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 apparent. This study focuses on the behaviour and capacity of water and waste water of steel tanks under multiple earthquakes to cover the aforementioned gap where the most critical parameters are investigated and useful conclusions are provided.

2. Description of model, seismic input and seismic sequence effects

2.1. Description of the model

The response of thin-walled cylindrical 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 Ref. [1,15,31], amongst others. A simplified yet reliable seismic analysis of cylindrical steel tanks is examined in this section. It is worth noticing that the examined approach is compatible with the aforementioned pertinent literature [5,9] and design codes [4], and does not involve complicated computational methods, e.g., the usage of special fluid elements for the simulation of water, etc.

Fig. 1 demonstrates an elevated cylindrical steel water tank with above-ground tank height, h_t, external radius *R*, thickness *s*, total height *h*, and fluid level *H*. Tanks can be characterized as 'tall' ($H/R > 1$) or 'broad' ($H/R \leq 1$) [31].

The aforementioned elevated steel tank can be reliably simulated for its seismic response using simplified models. More specifically, in the following a simple yet effective procedure that based on Minoglou et al. [1] and Malhotra et al. [31] is developed and executed. Thus, the tank of Fig. 1 can be represented by the structural model of Fig. 2. It is assumed, as it is adopted in everyday engineering practice, that the main-body of steel tank satisfies the geometric restrictions that have to do with the avoidance of local buckling of thin-shell structure, taking also into account the probable imperfections. Therefore, the nonlinear structural behaviour has mainly to do with the geometric and material nonlinearities of tank's substructure. Without loss of generality, two elevated steel tanks are investigated here. The data of the examined

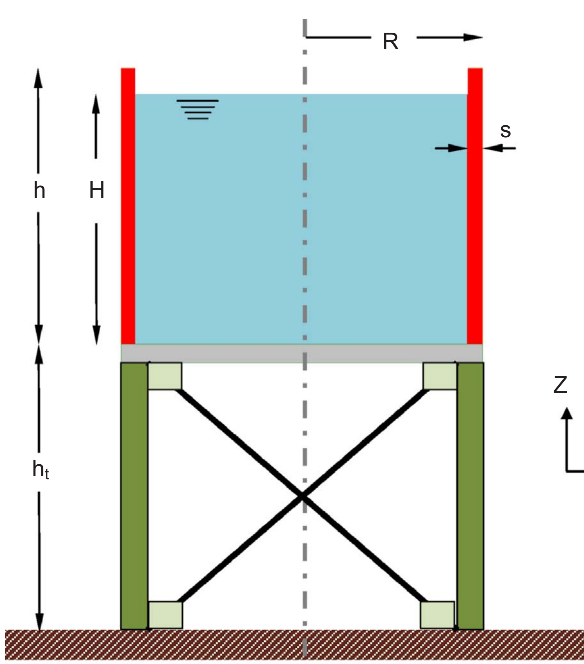

Fig. 1. Typical elevated steel water tank.

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 10 mm (top of the tank) to 20 mm (bottom of the tank) where an averaged thickness of shell, $s_{av.}$ = 15 mm is assumed.

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

The dynamic analysis of a structure requires the knowledge of characteristics of damping. In this study, it is assumed that the fluid oscillation has an inherent damping ratio equal to 0.5% and the steel tank equal to 2% [1,31]. The Rayleigh assumption is assumed for the construction of damping matrix where the aforementioned damping ratios, 0.5% and 2%, correspond to 1st mode (motion of convective mass of water) and 3rd mode (steel tank oscillation), respectively. Due to symmetry of geometry, boundary conditions and mass distribution, the 2nd mode is identical to the 1st mode (and it is presented in normal direction) and the 4th mode is identical to 3rd mode (and it is presented in normal direction, too). Table 2 presents the modal and damping characteristics for both tall and broad tank.

2.2. Seismic loading of steel tanks

The elevated steel tanks have been designed for according to EC8 [4] provisions. More specifically, these structures have been designed for the following loading combinations:

a) $1.35G + 1.50Q$
b) $1.00G + \psi Q + 1.00E$
c) $1.00G + \psi Q - 1.00E$

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 $\psi = 1.00$ in this study (that means tanks are completely filled during ground motion). In this study, the seismic action of the steel tanks under consideration is compatible with the provisions of Eurocode 8 [4] (Annex A, EN 1998-4). It should be noted that EC8 [4] focuses on rigid vertical cylindrical tanks and provides analytical formulae for calculating the impulsive and the convective pressures. It should be mentioned that all the modern seismic codes propose modelling the liquid-tank system by means of mechanical analogs, where liquid mass is divided into convective and impulsive masses, i.e., the seismic response of tanks appears to be a combination of convective and impulsive responses. Thus, although Eurocode 8 [4] uses the 'absolute summation rule', other codes, such as API650 [3], use the SRSS (square root of the sum of the squares) rule. In order to avoid the dependence or influence from the aforementioned rules, in this study, the time-history analysis approach is adopted for the simplified models of Fig. 2, where for these 2-DOFs systems are subjected to appropriate seismic records. More specifically, ten artificial accelerograms, compatible with the design spectrum of EC8, have been used, assuming soil type C conditions and design / peak ground acceleration (*PGA*) of 0.3 g. The response spectra of artificial accelerograms as well as the design spectrum of EC8 [4] are shown in Fig. 3

The seismic inelastic structural response of steel tanks can be obtained by the solution of dynamic equilibrium equation, which can be expressed in incremental form as [32]

$$M\ddot{u} + C\dot{u} + K^T u = -Ma_g \tag{1}$$

where M is the mass matrix, u the relative displacement vector, C the viscous damping matrix, K^T the tangent (inelastic) stiffness matrix, a_g