Thin-Walled Structures 50 (2012) 14–23

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Seismic analysis of steel liquid storage tanks by Endurance Time method

H.E. Estekanchi *, M. Alembagheri

Department of Civil Engineering, Sharif University of Technology (SUT), P.O. Box 11155-9313, Tehran, Iran

ARTICLE INFO

Article history:
Received 15 July 2010
Received in revised form
20 August 2011
Accepted 22 August 2011
Available online 18 October 2011

Keywords:
Endurance Time method
Steel liquid storage tanks
Seismic assessment
Dynamic pushover
Intensifying excitation

ABSTRACT

Endurance Time (ET) method is a time history based method for seismic evaluation of structures using intensifying dynamic excitation as the loading function. In this paper, application of this method in the analysis of steel tanks has been investigated. A methodology for practical application of ET method in seismic assessment of storage tanks has been presented. This methodology has been applied in three-dimensional nonlinear analysis of a particular anchored steel tank using Finite Element method, and results are compared with conventional codified design procedures. Results of the analyses indicate reasonable accuracy of the proposed method in estimation of seismic responses of steel tanks and its applicability in enhancing the design process of steel tanks considering various sources of complicated behavior. Comparative study of seismic response of the tank in anchored and unanchored states utilizing ground motions has been presented. Advantages and limitations of the procedure have also been discussed.

1. Introduction

A main objective in seismic design of structures is to make sure that the structure has acceptable performance when subjected to earthquakes with various intensities and probability of occurrences during its service lifetime. Various well-known codes in the last two decades have been trying to lead their design criteria to follow performance-based design concepts [1]. A milestone of this trend can be considered SEAOC committee's report. The performance level can be viewed as an acceptable damage state for the structure when it is subjected to an earthquake with specific intensity [2]. Design codes related to storage tanks have considered various performance levels, such as three earthquake risk levels in Iranian Oil Industry Seismic Design Guide (IOSG Code) [3].

Development of the performance-based design methods requires advancement of structural analysis methods to incorporate relatively complicated performance criteria. Time history dynamic analysis is a powerful and reliable method for seismic assessment of structures especially for those involving various sources of nonlinear behavior. In this method, dynamic behavior of tank is analyzed under earthquake accelerogram that is exerted to the base level of tank as a function of time, and response history of base shear, overturning moment, wall stresses and fluid wave height and other independent or derived response parameters are obtained. Selection of appropriate accelerograms and determination of tank responses under them considering nonlinear behavior of tank, result in accurate evaluation of tank performance.

Many regulations were introduced in design codes for utilization of earthquake accelerograms, such as satisfaction of code's design earthquake, considering soil profiles similar to construction site of tank, required minimum number of records, scaling of accelerograms, and specific procedure for their application to the tanks [3,4]. However, this method is the most time consuming method as compared with other analysis methods. In addition, in spite of good accuracy, complicated difficulties of this method have prevented its comprehensive utilization [5]. Consequently, researchers and engineers are looking for ways to improve analysis procedures by creating more effective methods with adequate accuracy, such as Pushover and IDA analyses that have their own advantages and disadvantages [6,7]. Endurance Time method (ET) is a new structural analysis method based on time history analysis utilizing predesigned intensifying dynamic excitation as a loading function. By subjecting the intended structure to a gradually intensifying excitation and monitoring its performance and response through the entire intensity measure of interest, considerable reduction in required computational demand as compared to conventional response history based analysis procedures can be achieved. In this paper, the basic principles of ET method as applicable to the analysis of storage tanks are reviewed; and afterward, practical application of ET method in seismic analysis of steel tanks using the proposed methodology is investigated. Application of ET method in the analysis of storage tanks and similar structures involving special structural forms such as shells interacting with fluids can pave the way for practical utilization of more reliable time-history based methods in the analysis and design of these types of structures.

* Corresponding author. Tel.: +98 21 66164212; fax: +98 21 66014828.
E-mail address: stkanchi@sharif.edu (H.E. Estekanchi).

0263-8231/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tws.2011.08.015

Nomenclature

D	tank diameter
E	modulus of elasticity of shell's material
ET	Endurance Time method
ETAF	endurance time acceleration function
g	ground acceleration
GM	ground motions
H	maximum height of contained fluid
I	importance factor
IOSG	Iranian Oil Industry Seismic Design Guide
m_p	contained fluid total mass
m_c	convective mass of fluid
m_i	impulsive mass of fluid
m_s	tank shell (wall) mass
m_r	tank roof mass
m_f	tank floor mass
MDOF	multi-degree of freedom systems
R_u	inherent overstrength and global ductility capacity of lateral resisting of impulsive mass
R_{uc}	inherent overstrength and global ductility capacity of lateral resisting of convective mass
R^2	points scattering indicator in a diagram
S_a	spectral acceleration
S_{DS}	spectral acceleration at period time of 0.2 s
SDOF	single degree of freedom system
STDEV	standard deviation
t	wall (shell) thickness
t_e	relative thickness of wall (shell)
T_i	fundamental impulsive period
T_c	fundamental convective period
Y	vertical distance from fluid surface to considered point
ρ	fluid density

2. A brief review of steel tanks seismic assessment

Thin walled structures exhibit complicated dynamic behavior and their seismic assessment is a challenging problem in earthquake engineering. These complications are magnified in case of steel tanks where the fluid–structure interaction issues are involved. Westergaard's researches in early 1930s could be considered as first studies about hydrodynamic pressures due to harmonic excitation [8]. He obtained hydrodynamic pressure on vertical rigid surface of a dam with infinite reservoir. First studies in the field of dynamic behavior of tanks were carried out assuming rigidity of wall and rigid connection of tank base to foundation. In 1934, Hoskins and Jacobsen studied vibration of rectangular tanks with rigid wall on nonflexible base that regarding to rigidity of wall and base they only obtained the dynamic response of contained fluid [9]. Housner in 1954 divided the fluid inside the tank into impulsive and convective parts [10]. The impulsive fluid could be assumed to move with the structure, and the convective fluid presents moving wave motion in the upper part. He showed that in most cases, major part of base shear and overturning moment is due to impulsive fluid. Based on convective fluid properties, sloshing motion of contained fluid free surface is determined. Edwards carried out research in the field of behavior and dynamic properties of tanks with flexible wall in 1969 [11]. He used Finite Element method in a computer analysis of tanks considering interaction of fluid and elastic wall of tank. In 1977, Veletsos and Yang showed that the assumption of rigid wall in tanks analysis leads to unreliable base shear and overturning moment [12]. Gupta and Hutchinson studied the effects of wall flexibility on the dynamic response of liquid storage tanks and indicated that for both shallow and deep tanks bulging frequencies decrease with reduction of wall thickness [13]. The dynamic pressure due to liquid sloshing has a maximum at the liquid surface level and a minimum at the bottom of the tank, and vice versa for the dynamic pressure due to bulging of the tank. They also showed that tank wall flexibility is an important parameter that considerably influences the dynamic pressure distribution in the bulging mode. Tedesco et al. in 1987 studied free vibration of cylindrical liquid storage tanks considering interaction of shell and liquid [14]. They indicated that the vibration of the convective fluid mass is unaffected by the vibration of the shell and stationary (impulsive) mass. In addition, it was observed that the vibration of the convective fluid mass is insensitive to shell flexibility. Gunawan et al. presented the free vibration characteristics of fluid-filled cylindrical shells on elastic foundations by a semi-analytical finite element method. They investigated the effect of fluid in a shell, shell geometries, and foundation parameters on the dynamic behavior of fluid-containing shells [15]. Recently, ambient vibration tests and finite element modeling of tall liquid storage tanks performed by Amiri and Yazdi showed good agreement between the numerical and experimental values of dynamic parameters [16]. They also showed that the tanks roof has negligible effect on the natural frequencies of vibration but it has significant effect on the mode shapes of tanks.

Barton and Parker used the Finite Element method for the evaluation of seismic behavior of unanchored tanks taking into account gap conditions for tank base uplifting [17]. Results of their research showed the importance of accurate attention to support conditions of tanks in seismic calculations. Because of impacts between base and tank floor due to uplifting, resultant forces and stresses are considerably greater than anchored state. Veletsos and Tang studied the soil–structure interaction effects on responses of laterally excited liquid storage tanks and showed that the effect of this interaction is negligible on sloshing of convective fluid [18]. Malhotra conducted researches on base uplifting of unanchored tanks. He indicated that base uplifting decreases the hydrodynamic forces on tank wall but increases the axial compressive stresses in the tank wall. In addition, the flexibility of base reduces the increasing rate of axial compressive stresses [19,20].

Tedesco et al. in 1989 appraised via the response spectrum technique the dynamic seismic response of flexible, liquid-filled cylindrical storage tanks and showed that impulsive and convective parts treat independently [21]. They presented a simple analytical procedure, applicable to both completely full and half-full tanks, which accurately predicts impulsive hydrodynamic wall pressures, shell stresses, base shear, and overturning moment. Their numerical comparisons illustrated the unconservativeness of the rigid tanks procedures that employed by many practicing engineers.

Hamdan reviewed the behavior and design guidelines of cylindrical steel liquid storage tanks subjected to earthquake motions [22]. He presented field observations during past earthquakes together with Finite Element analyses and published experimental results to assess the accuracy of design guidelines, with special emphasis on Eurocode8 [23]. He emphasized the areas where design guidelines on that time required further development, such as more realistic consideration of the effects of sloshing, hydrodynamic pressures and tank base support on axial compressive stresses, overturning moment, base shear and hoop stresses. Haroun and Bhatia by Finite Element analyses showed that the hoop stresses are increased by uplift of the tank base [24].

Ozdemir et al. in 2010 analyzed the anchored and unanchored steel tanks by application of nonlinear methods for fluid–structure