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Dynamic buckling of steel tanks under seismic excitation: Numerical evaluation of code provisions

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ABSTRACT

Many above-ground steel liquid storage tanks have suffered significant damages during past earthquakes. Such failures are due to several causes. The most common one is dynamic buckling. Several theoretical and experimental research studies were performed without solving this complex problem completely. Design codes such as AWWA-D100 and EC8 based their seismic standards on the recommendations given by some of these research results. The present contribution tries to evaluate these recommendations by using a numerical model with a robust and stable shell finite element. By using several seismic excitations and tanks with different geometrical parameter, this contribution tries to evaluate the PGA values that cause the tank instability. These numerical values are compared with standard code previsions. The obtained results confirm some code guidelines in the case of broad tanks, and show the need for improving them in the case of tall ones.

1. Introduction

Steel storage tanks are fairly common strategic constructions, as they represent the basic components in several industrial constructions especially in nuclear power plants. Unlike most structures, the storage tank weight varies with time due to the variable level of the stored fluid.

These vessels may contain substances at low temperatures (e.g. LNG) or corrosive products. Recently the storage tanks have suffered from the occurrence of catastrophic failures due to seismic shocks such as the Northridge earthquake in California 1994, the Kobe earthquake in Japan 1995 and that of Chi-Chi in Taiwan 1999.

The damages caused to these structures made them generally out of service. The emergency operations after an earthquake will be then particularly handicapped. These damages can also cause uncontrolled fires or environmental contamination in the case of flammable or toxic contents. The failures of these structures are manifested: by diamond or elephant's foot buckling, by uplift of their bases, by pipe damage, etc. Amongst these negative phenomena, dynamic buckling of tank walls remains the most common and the most dangerous one; according to the fragility report established by the American Lifelines Alliance [1].

This instability appears usually in two forms: the elephant foot buckling (EFB) – which is an outward bulge located just above the tank base – results from the combined action of vertical compressive stresses, exceeding the critical stress, and hoop tension close to the yield limit [2]. The elephant foot buckling bulge usually extends completely around the bottom of tanks due to the reverse in the direction of the seismic excitation [3]. The second form, called diamond buckling, is an elastic instability phenomenon due to the presence of high axial compressive stresses [2].

Fig. 1 illustrates these two types of instability. The safety of storage tanks against these serious seismic phenomena becomes, therefore, a crucial need. The international standards offer very few practical requirements to guard against the dynamic buckling of tanks due to a seismic loading. These provisions, some quite recent, have not sufficiently benefited of large scientific and practical evaluation.

Several analytical, experimental and numerical studies have been carried out to highlight the complexities associated with the behaviour of liquid storage tanks against the dynamic buckling.

An analytical method was developed by Uras and Liu [5] for the investigation of the dynamic buckling of liquid-filled tanks under horizontal excitation. The major conclusion of this contribution was the importance of the modal interaction in the axial and circumferential directions.

Experimental studies have been extensively carried out. The pioneering experimental work was performed by Clough [6] and Manos and Clough [7]. In 1982, Niwa and Clough investigated on the University of California shaking table the earthquake response behaviour and the buckling mechanism of a tall cylindrical wine

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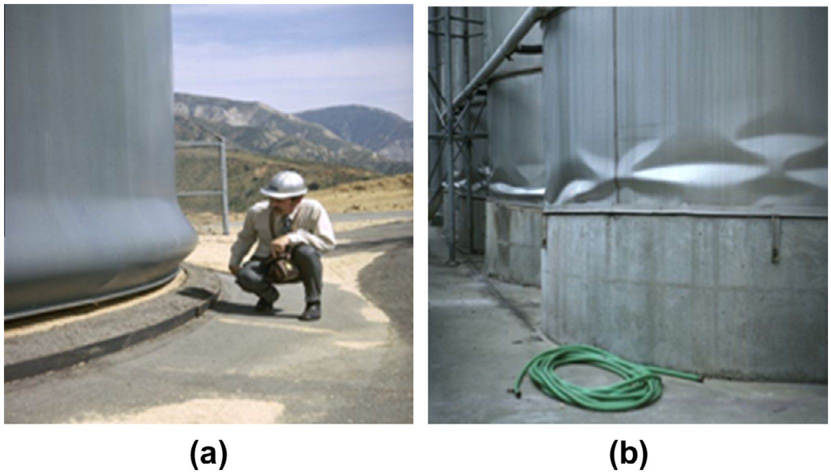

Fig. 1. (a) Elephant foot buckling, (b) diamond buckles [4].

storage tank similar to those damaged under the 1980 Livermore earthquake [2]. It was reported that the elephant foot buckling was the most common damage in broad tanks while tall tanks suffered a diamond shaped buckling spreading around the circumference. Niwa and Clough concluded also that the critical buckling stress assumed in API 650 and AWWA D100 standards for the steel tank design are rather conservative estimates of the buckling strength. The same authors investigated the damages on many unanchored oil storage cylindrical tanks caused by the 1983 Coalinga earthquake [7]. Housner and Haroun [8] and Haroun [9] investigated the dynamic response of full-scale liquid storage tanks with forced vibration tests. Chiba et al. [10] carried out experimental studies on the dynamic stability of a cylindrical shell partially filled with liquid, under harmonic excitation. It was found that filling tanks partially has a remarkable destabilizing effect in contrast with empty tanks.

Barton and Parker [11] investigated the seismic response of anchored and unanchored cylindrical storage tanks subjected to only the horizontal excitation by using the general purpose finite element computer code ANSYS. To allow the effects of the liquid, they considered both added mass concepts and displacement-based fluid finite elements. Their results confirm the importance of the base restraint conditions on the behaviour of storage tanks.

El-Zeiny [12] developed a finite element program, which uses an updated Eulerian_Lagrangian description of the liquid structure interface, in order to analyze the nonlinear dynamic response of unanchored cylindrical liquid storage tanks subjected to strong base excitation considering both large amplitude nonlinear liquid sloshing and fluid structure interaction. One of the main conclusions of this work is that the stress distribution around the circumference of broad tanks shows a stress concentration towards the principal diameter which parallels the earthquake excitation, leading to an amplified peak stress.

El-Bkaily and Peek [13] presented an algorithm that predicts the elephant foot location and the extent of its bulging using a Finite Element Method. The proposed simplified model was applied with success to analyze the example of one tank damaged during the 1977 San Juan earthquake.

Nachtigall et al. [14] analyzed the structural response of seismically excited vertical cylindrical tanks using Galerkin's approximations for cylindrical shells. Their results differ from those evaluated using EC8 and API 650 Standard. They recommend reconsidering these standard design provisions.

Using the finite element package ANSYS to model the tank-liquid system, Moslem and Saeed [15] studied the influence of the roof on the dynamic behavior of tanks. They confirm the benefice contribution of the roof to restrain the tank top against radials deformations.

The first numerical research dedicated to the evaluation of the peek ground acceleration (PGA) that causes the dynamic buckling is due to Virella et al. [16]. Using the general structural computer code ABAQUS, they examined the critical horizontal peak ground acceleration which induces the buckling of a set of anchored cylindrical tanks.

There are not many studies in the literature which criticizes tank seismic design codes. The well-known work in this area is due to Hamdan [17] who presents a review on the behaviour and design guidelines of cylindrical steel liquid storage tanks subjected to earthquake motion. More recently, Jaiswal et al. [18] have presented a study in which provisions of ten seismic codes on tanks are reviewed and compared. The conclusion of this study revealed that there are significant differences among these codes on design seismic forces for various types of tanks.

In the same subject, the seismic resistance of seven existed unanchored cylindrical oil storage tanks was calculated by Koller and Malhotra [19] according to EC8 and to the non-linear pushover analysis proposed by Malhotra [20]. They found that the EC8 cyclic plastic rotation constraint is more stringent than elephant-footing or elastic buckling of the shell. More recently, Naghdali et al. [21] have investigated several existing tanks using API-2008 rules and numerical FEM model based on ANSYS software. Their results have shown some imperfections in the API requirements.

To the author's knowledge, no evaluation of standard provisions concerning the dynamic buckling resistance of liquid storage tanks due to seismic excitation has yet been established. The aim of this paper is to do such an evaluation by numerical analysis using tanks of different geometrical parameters under three earthquake records. This work is also motivated by the need for the enhancement of the Algerian seismic code RPA (Règles Parasismiques Algériennes) [22] which has not contained any provisions for liquid storage tanks design yet.

2. Presentation of the numerical model

2.1. Wall and roof

The wall and roof are modeled in this study by using a general shell finite element with six degrees of freedom per node (DDSE9) developed locally and exposed in [23,24].