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Calculating the Earthquake Resistance Performance of a Water Tank with an Overhead Structure: A Review

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ABSTRACT
This research mainly deals with study of seismic performance of circular shaped overhead water tanks (OWTs) made of concrete material. Out of the two types of staging provided for OWTs, framed staging is considered. Moreover, the performances of OWTs resting on different soil strata such as hard soil, medium soil, and soft soil are taken into consideration in addition tothe OWTs with fixed base. Initially, to understand the seismic performance, eight tanks of different storage capacities have been studied. Since there is no specification for seismic analysis of overhead water tanks in the Indian code IS1893 (part 1):2016, the guidelines 'Indian Institute of Technology Kanpur- Gujarat State Disaster Management Act' (IITK-GSDMA) has been adopted for seismic analysis of OWT. It provides guidelines for structural idealisation of tanks for both empty and full conditions. It idealise the filled OWT as two degree of freedom system and they are impulsive and convective mode.

INTRODUCTION

This chapter deals with the basics of overhead water tanks, their types, guidelines available for their seismic analysis, and enhancing theirearthquake resistance. It also consists of a brief literature review on thepresent work.

GENERAL

Overhead water tanks (OWTs) are very essential for storing drinking water in the public distribution system and storing chemicals in the case of industries. Giving importance to the dynamic analysis of OWTs started after the occurrence of Chilean earthquakes in the year 1960. Since therequirement of water after the occurrence of an earthquake is an urgent need, the main job of the earthquake engineer is to ensure that water tanks are functional even after the occurrence of the earthquakes, failing which leads to big problems. Water tanks are classified into two types according to the type of staging used. They are shell tubular and framed structures. This research is focused on framed staging tanks.

The configuration of OWT resembles the performance of the cantilever beam. As the mammoth amount of mass is lumped at the top of the slender staging system, mainly filled water tanks, OWTs are highly susceptible to horizontal loads mainly due to earthquakes. There are two type of motions normally taking place in OWTs during an earthquake. The firstone is the motion of water stored with respect to the tank wall and another oneis the motion of the water tank as a whole with respect to the ground level. These motions induce the dynamic forces from the bottom to the top of the OWTs. Poor construction, heavy gravity load compared to conventional buildings, and improper design detailing leave the water tanks with minor cracks to Catastrophe of tanks.

The seismic performances of OWTs are very extensively investigated by many researchers experimentally as well as analytically (NZS-3106 2009, Kalani 2014, Haijuan *et al.* 2012). However, very few number of investigations are there regarding the dynamic factor namely the Natural Time Period (NTP), mainly influencing its seismic performances. Because the spectral acceleration seismic coefficient (Sa/g) is varying only with respect to NTP for the fixed damping ratio. Therefore, extensive caring is given on the two parameters, lateral stiffness and lumped mass. These two parameters, in turn, are varying with respect to various factors such as tank size, number of columns in the supporting system, number of horizontal bracing configurations, and height to diameter ratio and so these are factors influencing the performances of tanks significantly.

To gain sufficient knowledge on the factors influencing the seismic performances of OWTs, eight numbers of various existing tanks, meant for drinking water purposes, located in Tuticorin district, south India, had been collected. Table 1.1 shows the structural description of OWTs and The structural frames and their horizontal bracing configurations were shown in Figure 1.1 and Figure 1.2 respectively. Their plan, section, elevation, size and number of beams, columns, horizontal and vertical bracings, reinforcement detailing, the characteristic compressive strength of concrete and yield strength of steel reinforcement, storage capacity, total weight, the height of staging, and all other important structural parameters had been studied. The seismic performances of OWTs are very extensively investigated by many researchers experimentally as well as analytically.

LITERATURE REVIEW

Review on Linear and Nonlinear Seismic Performances ofOverhead Water Tanks

The dynamic responses of the OWTs due to ground accelerations may either be linear or nonlinear based on its Peak Ground Acceleration (PGA). The response reduction factor is the factor by which the actual base shear force, which would be generated if the structure were to remain elastic during its response to the DBE shaking, shall be reduced to obtain the design lateral force. Later on, knowledge of inelastic response spectra, reduction factor, and its determination of the SDOF system was collected.

Housner (1963a, b), Veletsos (1984), Priestley*et al.* (1986) gave a simplified dynamic analysis procedure. Pouyan *et al.* (2017) developed a new analytical method to find out the natural frequencies of OWTs using the configuration of the equivalent mass-spring model. It also showed that the fluid-structure-soil interaction influences the natural periods mainly on soft soil.

Dutta (2000) highlighted the importance of the problem of repetition of torsional failure of overhead water tanks in past earthquakes, mainly 1952 Kern County and recent 1993 Killari earthquakes. It was found out that the susceptibility of the OWT to this torsion-induced rotation might have amplified when the ratio of torsional to lateral natural period was approximately equal to unity. Moreover, if the ratio was within the critical range of 0.7 to 1.25, coupled lateral-torsional vibration would lead to the amplified displacement of structural elements. Closed-form expressions were also derived for calculating the base shear and base moment of beams as well as columns subjected to torsion and lateral force. These expressions were also used to observe that the framed stagings, designed mainly for resisting the lateral seismic force, might yield in such a way that plastic hinges were formed simultaneously in all columns leaving beams, if they are subjected to large rotational response and having the ratio close to unity. Such a yielding pattern would pave the way for the OWTs to be collapsed suddenly byforming a mechanism. Therefore, it was found out that torsional coupling is the main cause of failure for OWTs.
Borzia *et al. (*2001) recognized that displacement-based seismic design is a potentially lucid approach compared to forced-based practices. A well-controlled ground excitation due to an earthquake was considered to construct the inelastic displacement response spectra. The response reduction factors of displacement and the relationship between ductility and damping had been derived from the spectra constructed.

Luis *et al. (*2003) established the displacement demand, in terms of soil type, source to site distance, and magnitude, of SDOF systems from the elastic and inelastic displacement response spectra of an ensemble of ground accelerations due to various earthquakes. Finally, the relationship, inelastic displacement ratio made with soil condition, displacement ductility, and period of vibration, had been proposed.

Eleni & Michael (2004) studied the performances of elastic and inelastic structures with viscous damping systems to soft-soil and near-field ground excitation. Ductility demand of the single degree of freedom systems and three-story framed structures with and without providing linear and nonlinear viscous damping devices were studied and the results were compared with the conventional buildings.
Similarly, lateral displacement ductility demands of nonlinear single degree of freedom system using smooth (i.e., design) elastic response spectra due to ensemble of ground accelerations as well as response spectrum of individual ground acceleration were investigated by Farrow & Kurama (2004). Comparing the results, it was concluded that displacement ductility demand obtained by individual ground excitation provides unconservative results mainly for near-fault, soft soil, and survival level condition.

Hugo *et al.* (2007) proposed a numerical method to do the seismic analysis of cylindrical tanks considering nonlinear hydrodynamic effects. Here, the equations of motion in the physical domain were transformed into a well-defined computational domain. Then, a finite difference in cylindrical coordinates was used to get the numerical solution. Consequently, the seismic responses of the cylindrical tanks when subjected to ground accelerations due to the Mexico earthquake of September 19, 1985, were studied by this numerical formulation. Seismic responses in terms of base shear, base moment, and liquid wave height were studied. The effect of resonance under harmonic load was also studied. Finally, for design purposes, consequences on considering the effects of nonlinear hydrodynamic were drawn.

Karakostas *et al. (*2007) constructed elastic response spectra of displacement, velocity, and acceleration and inelastic response spectra ofstrength and displacement of a set of ground acceleration records from Greece. Response spectra had been constructed for various critical damping ratio and ductility levels. Subsequently, strength modification factors were proposed from the constant ductility response spectra using statisticalanalysis, and also the corresponding empirical formula had been suggested.
Tong & Zhao (2007) analyzed inelastic SDOF systems for themodified-Clough hysteretic model with stiffness degradation. 370 earthquake records from four different sites were considered. The seismic force modification factor and elastic strength design coefficient

were suggested. Empirical formulae were proposed for mean as well as 90% probability response spectra and these were found to be following the statistically obtained curves.

Halil *et al. (*2008) recalled the damages that happened in the industrial damages due to the occurrence of the 1999 Mw7.4 Kocaeli, Turkey earthquake. Habas plant providing liquefied gas to medical facilities and commercial plants was within 10 km from the fault line. He noted that when the earthquake took place, two of the three liquid-containing tanks collapsed.

Chen & Kianoush (2009) suggested the assumption of a consistent mass approach and the flexibility effects on the wall instead of lumped mass and rigid wall respectively and shape functions were assumed for the five- mode shapes of the tank wall. The reliability of the shape functions assumed was checked by two case studies, one is on the taller tank and another on the shorter tank. The results showed that the method suggested was accurate andit is necessary to consider two mode shapes to get the desirable results. It is aimed, having gone through a number of research papers, at achieving the seismic performance of the OWTs using response spectrum analysis.

George & Dimitri (2009) computed maximum inelastic displacement of the SDOF system from the corresponding maximum elastic displacement using the knowledge of the inelastic displacement ratio. Extensive studies were carried out using an effective and sophisticated method to determine the inelastic displacement ratio in terms of viscous damping ratio, the period of vibration, force reduction factor, the strain-hardening ratio, and soil types. Finally, it was found out that the inelastic displacement ratio was influenced significantly by repeated earthquakes or multiple earthquakes.

George (2010) studied the ductility demand spectra of multiplenear and far fault earthquakes for SDOF systems considering seismic sequence effects. The artificial sequence was considered since the lack of availability of seismic sequence records. To express the ductility demand in the function of the period of vibration, pre-post stiffness ratio, viscous damping, and the force reduction factor, 120 million dynamic inelastic analyses had been conducted. Finally, it is found that considering only design response spectra is not enough in estimating ductility demand and it leads to an underestimation of structural damages. Suchitra *et al.* (2011) insisted the importance of OWTs in the earthquake-prone region mainly after an earthquakeoccurrence. Seismic behaviour of 240 models of OWTs by varyingdifferent factors such as the soil conditions, height of tanks, and seismic zones were studied.

Alexandr *et al.* (2015) made a numerical simulation of the partiallyfilled thin cylindrical tanks.The sloshing effects for both linear and non-linear conditions were considered. Partitioned and simultaneous solution procedures were investigated, in addition to the fluid-structure interaction effects. Eventually, thecodal provisions results were discussed and compared with the results obtained from the software. Claudia *et al.* (2015) made a seismic assessment of heritage-listed twoOWTs, one is taller with framed staging and another one shorter with shaft staging.Time history analysis was adopted and different retrofitting techniques was suggestedfor each tank. The analysis showed a numerical collapse took place in the tallertank of framed staging, whereas tensile stress beyond the allowable limit attained in the large space of the shorter one of shaft staging.

Ghateh *et al.* (2015) did an approach to establish seismic response factors for tanks. Initially, 48 prototypes were selected and their pushover curves were drawn. These curves were used to determine the seismic response factors. It was found out that tank size is the significant factoramong all the factors affecting the seismic response factors of tanks. Eventually, it was concluded that the same seismic response factors shouldnot be used for all types of tanks and it should be based on the tank size.

Mousavi & Tariverdilo (2015) investigated the possibility of reducing the seismic demand of the exterior walls of the rectangular liquid storage tanks by providing the tuning internal walls. The responses of the system coupled with rigid external walls and flexible internal walls werederived. The fluid field was in the frequency domain. Ground accelerations from near-source as well as the far-field of the long period were considered. Eventually, it was found out that the seismic demand of exterior walls could be reduced by tuning the internal flexible wall mass.

Ruiz (2015) developed a computationally efficient numerical model in this research to evaluate the seismic performances of liquid storage tanks and it was more complex than the Housner model, a most popular approach. And it was applicable to OWTs of any kind of geometry. In the model proposed, the liquid was assumed to be irrotational, incompressible, and inviscid and its motion is fully idealized as the velocity potential function. Hence, Equilibrium and Continuity equations illustrating this motion take the form of Bernoulli and Laplace equations, respectively. 2D finite element scheme was used to solve the Laplace equation and was combined with the Bernoulli equation. From the examples considered it was found out that extensive parametric studies could be performed in the proposed model with small numerical effort. It was also found out that this model was suitable not only for analysis purposes but also for the design of OWTs.

Because of the simplicity of the nonlinear static analysis, i.e., pushover analysis over nonlinear dynamic analysis, it has been adopted by many researchers in recent years. Yonghui *et al. (*2015) attempted to investigate the reliability and applicability of this method by comparing its results with the results obtained from dynamic pushover analysis. 12

reinforced concrete structures of varying characteristics had been taken into account. They were subjected to ground accelerations due to natural and artificial earthquakes. Each ground acceleration was being scaled up until the structures got collapsed. Dynamic pushover curves were developed for all the 12 RC buildings from the results of more than one hundred inelastic dynamic analyses using a detailed 2D modeling approach. Finally, it was found out thatthere was a good correlation existing between the static and dynamic pushover analyses. In cases of significant errors, Fourier amplitude analysis was adopted and conservative assumptions were suggested.
Livaoglu & Dogangun (2006) presented a simplified procedure for the earthquake analysis of OWTs considering the fluid-soil-structure interaction effects. It was found out that dynamic analysis of OWTs adopting the concepts of lumped mass, leads to an underestimation of the base shear and overturning moment for both the condition of a fixed base and embedded soil condition. Therefore, this paper attempted to suggest an alternate method to tackle that problem.

Livaoglu & Dogangun (2007) considered the soil-structure interaction effects on OWTs resting on six different soil strata and the sloshing effects on the liquid inside the tanks. Seismic performances had beenstudied using Ansys software. Models with and without the embedment were analysed. It was found out that the roof displacement of tanks resting on soft soil was very high compared to that of stiff soil. Eventually, it was concluded that foundation effects were insignificant for very stiff soil.

Ramazan & Adem (2007) presented the seismic performances of the cylindrical OWTs with frame staging resting on various soil strata. The OWT and subsoil stratum were modeled using the finite element method. Various soil strata as per Eurocode EC-8 were taken into consideration. The response spectrum method including the modal superposition principle was used to analyse the OWTs. Results of OWTs resting on a fixed base were compared to that of tanks on elastic medium and it had been observed that the seismic response was influenced significantly based on the subsoil properties. It was concluded that when the stiffness of soil decreases, the effects of earthquakes increase.

Sekhar *et al. (*2009) attempted to examine the failure of OWTs due to the occurrences of medium to severe earthquakes. Initially, the impulsive lateral time period and the ratio of impulsive torsion to lateral time period were investigated including the effect of a soil-structure interaction effect, andit was found out that soil-structure interaction increases impulsive time periodand decreases the ratio of impulsive torsion to the lateral time period. It was mainly for tanks of shaft staging of lesser height, larger radius, thick wall, andtanks resting on soft soil.

Kianoush & Ghaemmaghai (2011) investigated the effects of the frequency content of an earthquake on the seismic performances of a rectangular tank using four different ground motions. A simple model is used to consider the foundation effects in tanks. It involved the adoption of six different soil types explained in the well-recognized earthquake codebooks. Seismic response quantities such as base shear, base moment, and sloshing effects by varying the soil properties under different ground excitations were calculated and the results were compared. It was found that the increment or decrement of the response quantities was based on the stiffness of the soil adopted.

Wang & Lee (2015) dealt with the performances of the stainless steel water tank subjected to impulsive loading. To activate the projectile withmaximum speed, a gas gun was used. The ultra-thin pressure sensors placed in between the airbag and water tank were used to record the pressure-induced on the water tank and the potentiometers attached at the back of the watertank were to record the displacement details. Two different, front and rear, plate thicknesses of the water tanks were taken into account. Besides, emptyas well as filled tanks were compared to study the effects of water on the performances of the water tanks under impulsive loading. Besides the experimental works, the finite element method was adopted to reproduce the

experiment and improve the current test method. Eventually, the experimentally vindicated finite element models were further used to investigate the effects of water in minimising the deformation of the water tank under blast loading

RESULTS AND DISCUSSION

GROUND ACCELERATIONS

Ground accelerations are selected based on the peak ground parameters, i.e, Gopeshwar and Bhatwari are having maximum PGA and theirvalues are 0.36 g and 0.253 g respectively. Ummulong and Mawphlang are having maximum peak ground displacement, i.e., 3084.722 mm and 2103.986 mm respectively. Bhuj is having peak value in all three formats and its PGA, PGV and PGD are 0.106 g, 450.9 mm/sec, and 2982.303 mm respectively. Ghansiali is identified as medium ground acceleration and its value is 0.118 g. The response spectrum of displacement, velocity, and acceleration are readily constructed for the six ground accelerations selected using prism software andit is accompanied by EDRS of the IS 1893:(part 1) 2016). Prism software is based on the Newmark β average acceleration method, i.e., (The manual calculation of seismic responses show the peak values of structural displacement, velocity, and acceleration of the tank 1 of NTP of 2. 9 sec for the damping ratio of 5% due to the Gopeshwar ground acceleration as -167.30077 mm at 7.06 sec, 467.77103 mm/sec at 4.84 sec, and 0.08078 g at 7.02 sec respectively. The acceleration response spectrum is normalized by dividing it by peak ground acceleration and it is along with the Displacement response spectrum is shown in Figure 4.1(a)-(b). The acceleration response spectrum is used for determining dynamic response(Sa/g) of OWTs and the displacement response spectrum is used for knowing

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