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SEISMIC RESPONSE OF ELEVATED WATER TANKS: AN OVERVIEW

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Abstract- ***Elevated storage reservoirs are the structures which need to remain functional after major seismic events and therefore should be designed accordingly to resist expected seismic vibrations. Depending upon the storage capacity and other considerations, these reinforced concrete tanks can be of different shapes. Failure of these structures adds to the misery of the affected population and adversely affects the post-earthquake relief operations. Extensive research on dynamic response of liquid filled tank traces its origin back to the middle of the last century. This paper summarizes the studies of seismic response for elevated water tanks.***

Key Words: : *Elevated Water tanks, Finite Element method, Dynamic Parameters, Degree of freedom, Seismic Response.*

1. INTRODUCTION

Elevated reservoirs are considered as important structures and need to remain functional immediately after a major earthquake event for relief operations and to control fire break outs etc. [8]. Elevation of the reservoirs is provided through staging. Staging generally has structural system comprising of columns and horizontal braces which transmits the load to the foundation. The poor seismic performance of reinforced concrete elevated water tanks under earthquake ground motions has been observed in past earthquake. Supports of number of elevated water tanks got damaged during past earthquakes in spite of moderate magnitude and large epi-central distances [22]. Therefore the columns and braces are critical parts of such structures and are also designed to resist wind and earthquake loads. Expected seismic load depends upon several aspects like seismicity of the area, soil type, dynamic characteristics of the structure etc. The dynamic characteristics of the structure - the natural time period and damping largely influence the expected seismic load [17]. According to seismic code IS: 1893(Part I): 2000, more than 60% of India is prone to earthquakes [12]. Seismic analysis of elevated water tanks differ from other structures in two ways: (i) at the time of seismic excitation, the fluid inside the tank exerts hydrodynamic force on tank walls and base and (ii) in comparison of other structures liquid containing elevated water tanks have low ductility and redundancy leading to necessity of increased design seismic forces [19]. Thus these structures required precise estimation of design earthquake load and careful seismic analysis.

2. SEISMIC RESPONSE OF ELEVATED WATER TANKS

Large number of papers has been published till date related to seismic response of elevated water tanks. Researchers used different types of model and analytical and experimental techniques to find out the seismic response of these structures. Such studies are being used to provide guidelines and appropriate methods to ensure safety of elevated water tanks as far as possible in the event of earthquake.

Chandrasekaran and Krishna [1965] proposed a single-DOF model for obtaining a satisfactory estimation of dynamic response of elevated water tanks. They found that during severe earthquake, provisions should be made in the design for energy absorption. Measurements of time period of concrete water towers indicate that the effective flexural rigidity changes considerably with the vertical load. For full tank, the nominal values suggested for I, E and L give time periods which were a very good approximation to the measured values. They observed that tank full is the most critical condition for the design of water tanks against earthquake forces. Ramiah and Gupta [30] also used single-DOF model to estimate dynamic response of elevated water tanks for different types of foundation soils.

Housner [1957, 1963] developed a model by using an approximate analysis of the hydrodynamic pressures exerted on the walls of rigid tanks subject to unidirectional horizontal seismic ground motion. He assumed the liquid, divided into two-mass system: a part of the liquid at the bottom of the container, known as the impulsive component behaves the same way as solid material while the liquid above it, known as, the convective component participates in sloshing with a different dynamics having long period of vibration. The liquid was assumed to be incompressible and undergo small displacement. Due to its implementation simplicity, the model has been adopted in many codes and standards with certain modifications.

Sonobe [1969] further reported application of Housner's model in seismic analysis of elevated water tank. Both free vibration and stationary vibration tests were performed on 1/10- 1/20 scale models of two elevated water tanks in this study. The first model was a cylindrical tank model having 60cm diameter supported by a frame which had several levels of rigidity. The second model was a spherical tank of the same size. Furthermore, a forced vibration test under the input of pseudo El-Centro NS 1940 record was carried out on the cylindrical elevated tank model. From the test, the dynamic response of the tank including maximum displacement and acceleration of the frame and maximum sloshing height of the stored water was measured. Experimental results were in good agreement with those obtained from the analytical solution using a Housner's simplified two-DOF system. In creating this equivalent model, the weight of the frame plus impulsive water was assumed to be rigidly fastened to the tank, while the weight of convective water was assumed to be attached to the tank by means of springs.

Shepherd [1972] also used a two-mass idealization model to represent the dynamic behaviour of elevated water tanks. The validity of the model was verified by comparing the analytical values with those of a simple dynamic test conducted on a pre-stressed concrete elevated water tank with tubular tower type staging. The equivalent water masses, the moment arms, and the effective spring stiffness were calculated using Housner's formulation. The predicted natural frequencies of the two modes of vibration obtained through analytical solution were compared with those measured through a simple pull-back test. The sloshing frequency of the water inside the tank was determined by hand shaking tests. The percentage equivalent viscous critical damping was determined from the decay of the free vibration test results as 1.3%. The results of the study indicated that the use of a two mass equivalent model provides satisfactory estimations of the natural frequencies of the elevated water tanks. Ifrim and Bratu [1969] and Garcia [1969] also used a two-DOF representation to investigate the seismic response of elevated tanks.

Haroun and Ellaithy [1985] presented an equivalent mechanical model for evaluating the dynamic response of elevated water tanks. A cross braced frame as well as a concrete pedestal tower were analysed. The effect of tank wall flexibility and both rocking and translational motions of vessel were included in the study. The vessel was assumed to be rigidly connected to the supporting tower that is no relative rotation could occur between the vessel base and the tip of the tower. Analyses indicated that the rocking component of vessel could have a significant effect on maximum shear and moment exerted at the top of the tower.

Following the collapse of a conical tank in Belgium during the 1970s, an experimental research work was carried out by Vandepitte et al. [1982] on the stability of conical tanks under hydrostatic loading. A similar elevated conical shaped water tower was studied by El Damatty et al. [1997a]. They used a finite element model for stability analysis of the liquid-filled conical tanks under hydrostatic loading. The model was capable of including both geometric and material non-linarites for examining the effect of geometric imperfection on the stability. The effect of such imperfections was modeled by introducing initial strains into the finite element model of the tank before applying the loads.

Joshi [2000] presented an equivalent mechanical model for seismic analysis of rigid Intze type tanks under horizontal acceleration. Model parameters were evaluated for a wide spectrum of tank shapes and compared with those of the equivalent cylindrical tanks having same storage capacity volume. Fluid pressure was calculated using linearized potential flow theory. The fluid was assumed inviscid and incompressible and the sloshing height was assumed to be small. Furthermore, in developing the mechanical model only first sloshing mode was taken into account. It was concluded that the associated errors due to the use of equivalent cylindrical tank model instead of the original Intze tanks were negligible. As a result, for seismic design applications, the Intze tank models may be replaced by the equivalent cylindrical models without loss of accuracy.

In another study on seismic behaviour of elevated conical steel tanks was studied by El Damatty et al. [1997b, 1997c] developed a numerical model in which the tank wall was modeled by shell elements and the fluid effect was considered using the coupled boundary-shell element technique. Only the impulsive component of hydrodynamic pressure was considered. Several tank models classified as tall or broad according to their aspect ratio (tank radius/height) were analyzed. The supporting structure was simulated by linear springs added to the vessel base. The vessel was also prevented from rocking. The models also consider effects of both material and geometric nonlinearities. Both free vibration and non-linear time history analyses were carried out. It was concluded that elevated conical tanks, especially the tall tanks, are very sensitive to seismic. It was also indicated that the vertical ground motion contributes significantly to the dynamic instability of conical elevated tanks and should therefore be considered for seismic design of such structures. Sweedan and El Damatty [2005] investigated the dynamic response of purely conical tanks under vertical acceleration. It was shown that vertical excitation of such tanks could cause significant increase in the compressive meridional stresses generated in the tank walls.

The dynamic characteristics of elevated water tanks in which tank consisted of a truncated cone having a top superimposed cylindrical cap were identified experimentally in later studies by El Damatty [2005]. This study was the first experimental study carried out on a small-scale liquid-filled conical vessel. The fundamental frequencies as well as the frequencies of cosθ-modes (modes during cross-section of tank remains circular) of vibration were determined using shake table test. The experimental values were compared with those obtained from the analytical and numerical methods and in general an excellent agreement was observed. It was found that the cos(θ)-modes which lead to base shear and overturning moment in tanks subjected to seismic motions, show themselves as higher modes of vibration.

To further simplify the seismic analysis of elevated tanks, Sweedan [2009] proposed an equivalent mechanical model to duplicate forces induced in combined elevated tanks (vessel consisting of truncated cone and a superimposed top cylindrical cap) subjected to vertical ground acceleration. The proposed model was able to consider the flexibility of the tank wall. The stored liquid was modelled as flexible and rigid components. The flexible component was associated with the vibration of the tank walls, while the rigid component vibrated in synchronism with the base excitation. Parametric analyses were performed to evaluate the natural frequencies of the axisymmetric modes of vibration. The contribution of the stored liquid mass to the impulsive response was also determined by performing modal analyses.

Moslemi et al. [2011] addressed the difficulties associated with modeling of the tanks having complex geometries and evaluated the performance of conical elevated tanks under seismic motions. The Finite Element technique was employed to estimate the seismic response. Both time history and free vibration analyses were carried out. The effects of liquid sloshing and tank wall flexibility were considered in the proposed Finite Element Method. The obtained results were also compared with those obtained by current practice as recommended by American Concrete Institute and American Society for Civil Engineers. In this the accuracy of the method was also verified by comparing the obtained results with experimental and numerical values available in the literature. Modal Finite Element analyses resulted in natural frequencies and effective water mass ratios very close to those obtained from Housner's formulations. The results of the study also showed that the current practice could predict the dynamic response of elevated water tanks with reasonable accuracy.

Shenton III and Hampton [1999] studied the seismic response of base isolated elevated water tanks using a discrete three-DOF model. The natural frequencies and mode shapes of the isolated structure were determined and response spectral analyses were carried out. Isolation system was considered to be linear elastic. Furthermore, the tank walls were assumed to be rigid and the effect of rocking of the tower on dynamic response was ignored. Isolation bearings were assumed to be rigid in the vertical direction. Results of the isolated tank models were compared with those of the corresponding fixed base models and it was concluded that the base isolation was effective in reducing the seismic response of the liquid-filled elevated tanks. It was also shown that isolation was most effective for the smallest capacity tank.

Shirmali and Jangid [2003] investigated the seismic behavior of base isolated elevated tanks under real earthquake excitations using a four-DOF model. The isolation system considered was lead-rubber bearings. The fluid domain was modeled as lumped masses. Isolators were assumed to be rigid in the vertical direction and therefore the effects of uplift and rocking were not considered. It was observed that compared to non-isolated elevated tanks, the seismic response of the isolated tanks was significantly less. In addition, a simplified decoupled analysis was proposed in which the motion of tower structure was assumed to be rigid under seismic excitation. This assumption led to a simplified two- DOF model and two single-DOF models. It was concluded that this simplified method could accurately estimate the peak seismic response of the isolated elevated tanks with less computational efforts.

Later, Jadhav and Jangid [2004] investigated the dynamic behaviour of liquid storage tanks isolated by elastomeric bearings and sliding system under real earthquake records. The fluid domain was modelled as sloshing, impulsive, and rigid lumped masses. Newmark's method was used to solve coupled differential equations of motion in the incremental form. Aspect ratio of the tank and the time period of the isolation system were the important parameters considered. It was observed that elastomeric and sliding systems both were competent in lowering the earthquake forces of the tanks but elastomeric bearing plus lead core was found to work well in comparison to other systems. Further, for assessment of seismic response of base-isolated liquid storage tanks an approximate model was advised. By comparing proposed approximate method and exact tactic, it was seen that proposed approximate analysis gives satisfactory response estimates. The same model was there employed to study the seismic behaviour of liquid storage tanks subjected to near-fault ground excitations [Shirmali and Jangid (2003)].

Shekari et al. [2009] further investigated the seismic behaviour of isolated cylindrical liquid storage tanks under horizontal ground motions in a 3-D space. The structure was modelled by shell elements while the fluid domain was simulated using the internal boundary elements. The base isolation system was modelled by bilinear hysteretic elements. It was indicated that the dynamic response of isolated tanks reduce significantly as compared to the fixed base tanks. However, it was observed that the liquid free surface displacement was more moves in base isolated tanks. It was also concluded that the base-isolation system with lower stiffness was more effective. However, a minimum stiffness needs to be maintained to ensure the tank stability

Jain and Sameer [1990] reviewed the Indian Standard (IS) code provisions for seismic design of overhead water tanks. For water tanks due to absence of an appropriate value of performance factor code gives low seismic design force. For the determination of time period simple expressions were derived which allow calculation of lateral stiffness while incorporating beam flexibility. These expressions are based on portal method which has been developed to incorporate flexibility and 3-D behaviour of staging.

Later Jain and Medhekar [1993] given suggestion to modify IS: 1893-1984. The major revisions suggested are: (i) Provisions to incorporate analysis of ground supported tanks with rigid and flexible walls. (ii). Two or three degree of freedom idealization should be used instead of one degree of freedom idealization. (iii) Use 3.0 performance factors for all types of tanks. (iv) Flexibility of bracing beams should be included for calculation of lateral stiffness of tanks. (v) Convective hydrodynamic pressure's effect should be incorporated in dynamic analysis of water tanks. (vi) For design simplified equivalent hydrodynamic pressure distribution should be used.

In addition to Soon after Jain and Sameer [1993] also suggested some additional revisions which were: (i) include accidental torsion's effect in dynamic analysis. (ii) Using expression given for calculation of sloshing height of water. (iii) Considering the flexibility of wall for arriving at hydrodynamic pressure in the tanks.

Jaiswal and Jain [2005] identified the limitations and flaws in the provision of IS 1893:1984 and provide suggestions, which are: (i) Use of design horizontal seismic coefficient as given in IS 1893 (Part1): 2002 and proposed values of importance factor (*I)* and response reduction factor (R) (ii) Use of spring-mass model of Veletsos which is common for tanks with rigid and flexible wall (iii) Use of the modified expressions for convective hydrodynamic pressure and sloshing wave height and (v) Consider effect of vertical ground acceleration, critical direction of seismic loading and buried tanks are included

3. CONCLUSIONS

Elevated Water Tanks are considered to be important structures as it need to remain functional even during major seismic event. Large number of studies has been carried out on various aspects of seismic analysis and design of elevated water tanks. It is observed that researchers have used rigorous finite element models to find the seismic response. The simplified models developed subsequently were validated by comparing the results with rigorous analytical models or experimental study on scaled tank models. This paper reviewed some of the published worked. Following are the conclusion of this literature survey-

1. Elevated water tanks had been modelled as single degree of freedom and two-degree of freedom system.
2. Seismic stability is investigated for three condition viz (i) empty condition, (ii) partially filled condition and (iii) full tank condition and it is seen that third condition is most critical one.
3. SDOF results into acceptable estimation of seismic response of elevated water tanks and has been used by designers.
4. Flexibility of bracing should be considered for dynamic analysis of elevated water tanks.
5. Two-DOF proposed by Housner finds to result in more realistic estimation of seismic response.
6. Aspect ratio is an important parameter affecting significantly the hydrodynamic forces on the tank's wall.
7. Vertical ground motion contributes significantly to the dynamic instability of conical elevated tanks
8. Experimental study on prototypes on different types of elevated water tanks is lacking.
9. Parameters like importance factors, response reduction factor need to decide carefully.
10. Base isolation method is competent in reducing seismic response when stiffness of base isolators is low.

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