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New Lateral Load Pattern for Estimating Seismic Demands of Elevated Water Tanks Supported on Concrete Shaft

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Abstract—**Up to now, few studies have been done on seismic behavior of elevated water tanks, despite the necessity of water tanks for consuming water and firefighting, especially after earthquake. The scope of this paper is to propose new lateral load patterns to evaluate seismic responses of elevated water tanks supported on concrete shaft and also modeling the structures using simple models such as frame elements, Housner model and Cone model rather than rigorous methods. In this regard, a shaft supported elevated water tank is simulated by considering the soil-structure and fluid-structure interactions. Then the effects of soil type variations on these responses are investigated. By Incremental Dynamic Analysis (IDA) the exact responses of this structure are studied under an ensemble of ground motions. Thereafter, Nonlinear Static Analysis (NSA) named as Pushover is performed by variation of lateral load patterns. At the end, the more reliable lateral load patterns are proposed based on comparison of IDA, as an exact solution and those obtained using Pushover analysis. The results demonstrate the accuracy of proposed lateral load patterns.**

Keywords— **Incremental Dynamic Analysis (IDA), Nonlinear Static Analysis (NSA), Pushover, elevated water tanks, soil-structure interaction, fluid-structure interaction**

I. Introduction

Water tanks normally are used for drinking and firefighting. For increasing the head of water, engineers use elevated water tanks. Failure of these structures may increase the human losses and economical damages. Nevertheless few studies have been done on seismic behavior of elevated water tanks. For assessing the effects of earthquake on the structure both methods including Nonlinear Response History Analysis (NL-RHA) and Nonlinear Static Analysis (NSA) are used. But selecting and scaling an ensemble of ground motions is fraught with several unresolved issues. Thus, in this study new lateral load patterns for using in NSA (Pushover) are proposed that can estimate the dynamic capacity curve. The results demonstrate the accuracy of proposed lateral load patterns.

For modeling these types of structure the ordinary method is to model the soil, water and structure as a whole using the elements based on finite elements method. These elements are accurate for modeling these types of structures but in practical projects, engineers usually tend to use simplified methods because using these elements is complex and especially needs a lot of time for modeling and analysis. Thus, in this study it is tried to model the structure as simple as possible to be useful in practical projects.

In this regard, frame elements are used for modeling the shaft and for considering the nonlinearity effects of materials, some plastic hinges are assigned in the shaft length. The earthquake motion excites the liquid of the tank. A part of the liquid which moves with the body of the tank is called impulsive mass and the other part of the liquid which moves independently is called convective mass. Also, effect of soil flexibility is important in modeling these types of structure since this effect can change the distribution of inertial forces and may increase the possibility of tensile stress in the structure [1]. For considering this effect, some springs and dashpots are used below the foundation. These springs and dashpots can estimate the damping and stiffness of the soil accurately and can consider the effect of wave propagations.

Here, in this study, for designing of the tank, it is assumed that the tank is located on soft soil type E according to ASCE/SEI 7-10 [2] which is more critical than hard soil [3]. Also the displacements and the stress ratios are controlled in soft and stiff soils to take into account the effect of soil flexibility [4] and [5]. Furthermore the influence of soil flexibility in two conditions, full and empty tank, is considered [1]. In all cases there was not any point with tensile stress. The elevated water tank with the capacity of 150m^3 in four different types of soil is assumed in this investigation. Then lateral load patterns for Pushover analysis are proposed which are compatible with the dynamic capacity curves.

II. Assumption and Modeling

In this paper the effects of four different types of soil behavior for an elevated water tank with 150m^3 capacity are evaluated. The tank is supported on a concrete shaft with external diameter of 2.7m and thickness of 0.35m and the elevation of 20m from top of the foundation. Diameter of the cylindrical tank is 8m with a thickness of 0.2m. The thicknesses of the bottom and top tank slabs are 0.25m and 0.2m respectively. The water height is supposed to be 3.1m and its free board is 0.4m. The structure is erected on a cylindrical foundation with a radius of 5m and thickness of 1m. All concrete parts made from ordinary concrete with ultimate strength of 240kgf/cm^2. The tank is loaded according to ASCE/SEI 7-10 [2] for Nevada State near the vicinity of Las Vegas and designed according to ACI350.3-06 [6] and ACI371R-08 [7]. Fig.1 shows the whole structure model containing soil-structure-fluid interaction.

A. *Shaft Modeling*

The tank shaft is divided into 10 equal parts and is modeled using frame elements. Plastic hinges are assigned at the beginning of each part according to ASCE/SEI 41-06 [8]. These hinges can consider the interactions of axial forces and moment rotations. This assignment is utilized to cause nonlinear behavior along the shaft. Total body of the tank including top and bottom slabs and side wall is assumed to be rigid and the mass of each part of them is centralized at series of local points that offers identical mass and mass moment of inertia with the continuous model.

B. *Fluid-structure interaction*

The wall of the tank is assumed to be rigid and modified Housner model is used to consider fluid-structure interaction [9]. The tank water is divided into two lumped masses, impulsive and convective parts with the specific heights from the bottom of the tank. The impulsive part is considered to be rigid and is stuck to the tank wall. The convective part is connected to the tank wall by two springs to consider fluid-structure interaction with sufficient accuracy in engineering problems [10]. Equations (1) to (5) show the relations for calculation of masses and heights of masses and springs stiffness. In calculation of h_0 and h_1, for considering the effect of water pressure on bottom slab in addition to pressure on side wall, it is recommended to take α=1.33 and β=2, otherwise it is offered to take α=0 and β=1. In elevated water tanks the total moment of the tanks, effects on the shafts and the influence of the moment arising from bottom slab pressure is obvious. So for elevated water tanks, α=1.33 and β=2.

$$M_0=M\,\frac{\tanh 1.7\frac{R}{h}}{1.7\frac{R}{h}}. \tag{1}$$

$$M_1=\frac{0.71\times\tanh 1.8\frac{h}{R}}{1.8\frac{h}{R}}M. \tag{2}$$

$$k=\frac{4.75gM_1^{\,2}h}{MR^2}. \tag{3}$$

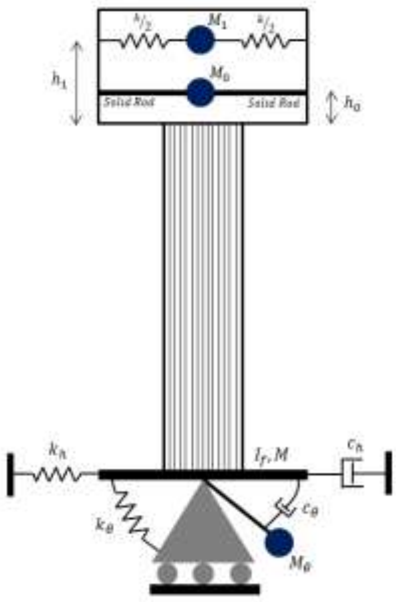

Figure 1. Structure model with soil-structure-fluid interaction.

$$h_0=0.38h\left(1+\alpha\left(\frac{M}{M_0}-1\right)\right). \tag{4}$$

$$h_1=h\left(1-0.21\left(\frac{M}{M_1}\right)\left(\frac{R}{h}\right)^2+0.55\beta\frac{R}{h}\sqrt{0.15\times\left(\frac{RM}{hM_1}\right)^2-1}\right). \tag{5}$$

Here, M is the total mass of tank water, R is the radius of the tank, h is the height of the water, M_0 is the impulsive mass, M_1 is the convective mass, h_0 is the height of the impulsive mass from the bottom, h_1 is the height of convective mass from the bottom and k is the spring stiffness. α and β are as above.

C. *Soil-structure interaction*

Cone model is used instead of methods based on finite element methods for modeling the soil-structure interaction. Finite element based method requires extra time which is suitable mostly for case studies while Cone model reduces time consuming and is more suitable for parametric studies. For this purpose Cone model with adequate accuracy in engineering problems is used [11]. This model assumes that foundation acts as a rigid and soil behaves as a homogeneous half-space. In this paper, the mass density of the soil is equal to 1800 kg/m^3 and the Poisson coefficient of the soil is assumed to be 0.3. Equations (6) to (10) show the soil parameters used in cone model.

$$k_h=\frac{8\rho V_s^{\,2}R}{2-\nu}. \tag{6}$$

$$k_\theta=\frac{8\rho V_s{}^2R^3}{3(1-\nu)}. \tag{7}$$

$$M_\theta=\frac{9\rho\pi R^5(1-\nu)^2}{64(1-2\nu)}. \tag{8}$$

$$c_h=\rho V_s A. \tag{9}$$

$$c_\theta=\rho V_p I_f. \tag{10}$$

Here, R is foundation radius, A is foundation area, h is foundation thickness, M is foundation mass, I_f is foundation mass moment of inertia, ν is Poisson coefficient, V_S is soil shear wave velocity, V_P is dilatational wave velocity, ρ is soil mass density, k_h is translational stiffness, k_Θ is rotational stiffness, M_Θ is mass of internal degree of freedom, C_h is translational damping and C_Θ is rotational damping.

III. Ground motion characteristics

Seven ground motions are selected from the strong ground motion database of the Pacific Earthquake Engineering Research Centre (PEER) [12]. The selected ground motions are far-field records, and are corresponded to locations with at least 12km far away from a rupturing fault. Each earthquake record scales to different acceleration levels in order to use in IDA. The frequency of each earthquake record and the main characteristics of the record remain steady during the scaling process. Seven records are used in order to decrease the sensibility of the structural response to a special characteristic of each record. Table I shows the list of used ground motions and their characteristics.

TABLE I. LIST OF GROUND MOTIONS USED

Earthquake name	Station Name	Station Number	Comp (deg)	Year	PGA (g)
Duzce, Turkey	Lamont	1061	E	1999	0.134
Northridge	LA- Baldwin Hills	24157	90	1994	0.239
Trinidad, California	Rio Dell Overpass, FF	1498	270	1980	0.147
Victoria, Mexico	Cerro Prieto	6604	45	1980	0.621
Hollister	SAGO South-Surface	47189	295	1986	0.090
Imperial Valley	Parachute Test Site	5051	315	1979	0.204
Morgan Hill	Carralitos	57007	310	1984	0.109

IV. Analysis and Discussion of the results

Structure dynamic capacity curve for each record is obtained from Nonlinear Response History Analyses (NL-RHAs) using SAP2000. Subsequently a curve representing the average of these seven curves is obtained for a soil type. By repeating this process for all four soil types with shear wave velocities of 175, 300, 550, 1100m/s, average structure dynamic capacity curves for each types of soil are achieved.

Fig. 2 illustrates that as shear wave velocity increases, structure shows less resistance. This is due to soil-structure interaction model which includes wave propagations in itself.

Conducting a series of pushover analyses using current lateral load patterns and bearing in mind the previous studies, new lateral load patterns are proposed which are more compatible with structure dynamic capacity curves obtained from IDA. These lateral load patterns are divided into two linear and nonlinear parts. Linear part is appropriate for first section of dynamic capacity curve and the nonlinear part is suitable for second part of dynamic capacity curve. Generally for the linear part, as the soil hardness increases, appropriate load pattern tends from uniform load pattern to concentrated load pattern.

A. *Pushover Procedure*

Step 1: Push the structure using uniform load pattern to collapse point (the point at which structure collapses). Then record the base shear-roof displacement diagram, Fig. 3.

Step 2: Convert the base shear-roof displacement diagram obtained from Step 1 into bilinear diagram using FEMA 356 [13] procedure.

Step 3: Record the corresponding displacement at the diverted slope in Step 2. Once more, push the structure using uniform load pattern to that resulted point.

Step 4: For nonlinear part, push the structure using the following proposed load pattern from resulted point in step 3 to collapse.

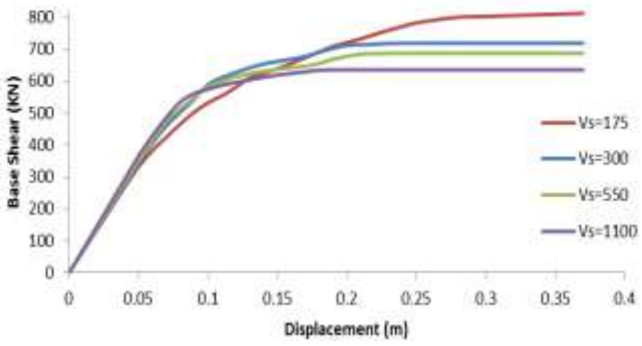

Figure 2. Capacity curves of various soil types.

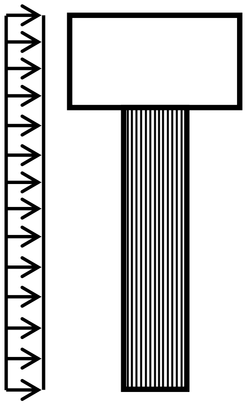

Figure 3. Uniform load pattern for pushover analysis (linear part).

As it is shown in Fig. 4, proposed load pattern consists of a uniform load along the shaft and a couple joint forces at the bottom and top of the tank. By assuming the magnitude of uniform load along the shaft as unit, the magnitude of point force at the top and bottom of the tank is calculated utilizing (11). Here L is the shaft length.

$$E=L\,\frac{\text{tank mass}+\text{impulsive mass}+\text{convective mass}}{(\text{shaft mass})}. \qquad (11)$$

Step 5: Fig. 5 shows equivalent structural dynamic capacity curve achieved by joining the base shear-roof displacement from step 3 and 4.

V. Summary and Conclusions

In this article, several IDAs on an elevated water tank having 150m^3 capacity, with four different soil types (different shear wave velocity) are performed. Average dynamic capacity curve of each soil type is obtained. Then lateral load patterns for Pushover analysis are proposed which are compatible with the dynamic capacity curves. By interpreting the results, following conclusions can be extracted:

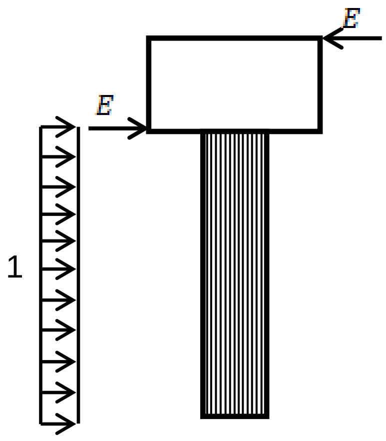

Figure 4. Proposed load pattern for pushover analysis (second part).

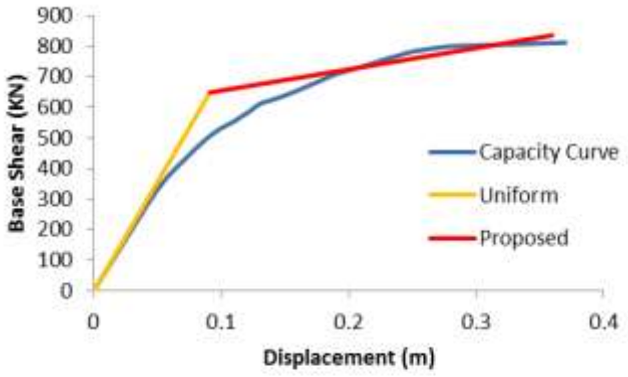

Figure 5. Resulted curve, Uniform for linear part and Proposed for nonlinear part.

As it is shown in Fig. 2, by increasing the shear wave velocity of soils, which is equivalent to soil hardening, structural resistance decreases due to wave propagations effect.

As it is illustrated, the structure behavior is so sensitive to the soil type and especially to the soil-structure interaction model. In this investigation, the structure situation has become more critical by soil hardening. So it is recommended firstly, in practical projects, assessments for determining the soil type is essential. Secondly, soil flexibility effect should be considered and finally as far as possible, those models for soil-structure interaction should be used which are more compatible with reality.

According to the nonlinear static analysis diagram, it is understood that this diagram at the beginning part of the linear section and at the end of the nonlinear section is compatible with the structure capacity curve, but it has some errors in the area that structure diverts from linear to nonlinear situation. However the accuracy of proposed load patterns is acceptable.

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