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Strength and Ductility Assessment Method for Elevated RC Water Tanks

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***Abstract*—Failures of elevated water tanks subjected to earthquake forces have been reported from many parts of the world in the past. Yet, a large number of elevated water tanks in Sri Lanka have not been designed for possible earthquakes whether they are minor or moderate in magnitude. When Intze type water tanks are considered, a huge mass is concentrated on top of the cylindrical shaped supporting structure. Therefore, this kind of structures can be conveniently modelled as a single degree of freedom system. In this study, pushover analyses were conducted using three-dimensional finite element model to develop bilinear load-deformation model based on equivalent energy criterion. With the developed bilinear model, nonlinear time history analyses of equivalent single degree of freedom system were conducted to obtain displacement demands. The variation of displacement demands of 72 cases covering different tank heights, capacities, shaft reinforcement ratios are presented.**

Keywords—Nonlinear time history analysis, nonlinear pushover analysis, lateral displacement, displacement demand

I. INTRODUCTION

Sri Lanka is generally considered to be located in an earthquake free region. However, recent ground shaking events occurred in and surrounding areas of the country alarmed the seriousness of consequences if unexpected ground shaking occurs in the country in future. Sri Lanka has vast number of elevated water tanks situated in whole parts of the island. The elevated water tanks are highly vulnerable even to a minor earthquake owing to their intended use. When subjected to earthquake loads elevated water tanks can fail due to various types of structural failures. Many such failures have been reported around the world. Yet, many elevated water tanks in Sri Lanka have not been designed even for possible minor earthquake loads. The dynamic behaviour of these structures significantly differs from that of static loads and needs careful and thorough analysis if seismic design provisions are to be imposed in design codes.

Elevated water tanks had poor and occasionally catastrophic seismic performance during many past severe earthquakes in many countries in the world. Number of research studies investigating the non-linear seismic response of Reinforced Concrete (RC) elevated water tanks have been conducted in the past. The response depends on many factors such as geometry and dimensions of the tank, water level (i.e., fully-filled, partially filled or empty), fluid-structure interaction, soil-structure interaction, magnitude and duration of the ground shaking. When partially-filled tanks are considered, modelling should be done by incorporating dynamic effects due to sloshing. Two mass models proposed by Housner [1] was one of the first models that include impact loads due to sloshing of water. This model has been commonly used in the most of the international codes. The main feature of this model is that the pressure generated within the fluid due to the dynamic motion of the tank was separated into impulsive and convective parts. When a tank containing liquid with a free surface is subjected to horizontal ground motion, both the tank wall and liquid subjected to horizontal acceleration. The liquid in the lower region of the tank behaves like a mass that is rigidly connected to the tank wall. This mass is called impulsive mass which accelerates along with the wall and induced impulsive hydrodynamic pressure on the tank wall. The liquid mass in the upper region of the tank undergoes sloshing motion. This mass is termed as convective mass and exerts convective hydrodynamic pressure on the tank wall. The base shear and overturning moment of tank structures can be determined using this model.

Algreane et al. [2] studied the fluid structure interaction due to dynamic response of elevated concrete water tank. In this study, the impulsive mass was divided by several numbers and attached along the circumference of the cylindrical wall at the level of the centre of gravity of the empty container. It was concluded that the suggested method of adding impulsive mass to the walls of tank does not affect significantly the dynamic behaviour of elevated tanks, both of the circular and rectangular shapes.

Early work by Epstein [3], Edwards [4], and Veletsos [5] conducted further studies on seismic design and dynamic analysis of liquid filled tanks by considering factors like tank flexibility and hydrodynamic forces. The effects of wall flexibility, soil-structure interaction, and sloshing motion on behavior of tanks subjected to ground accelerations were studies using techniques such as finite element analysis and computational fluid-structure interaction techniques.

Moslemi et al. [6] modelled liquid filled water tanks using finite element technique and both time history and modal analyses were carried out. Fluid domain was modelled using displacement based fluid elements and tank wall flexibility and sloshing effects were incorporated in the analysis. The complexities associated with modelling of conical tanks were also discussed.

In Intze type water tanks a huge mass is concentrated at top of the cylindrical shaped concrete supporting structure. Therefore, the structure can be modelled as single degree of freedom (SDOF) system by incorporating accurate stiffness and damping of the supporting structure. The main objective of this study is to establish a simplified but reliable and accurate analysis procedure to assess the safety of existing elevated water tanks subjected to horizontal ground accelerations. The proposed analysis is based on the concept of equivalent SDOF system in which the stiffness is computed using pushover analysis of water tank using three dimensional finite element model. Material models incorporating material nonlinearity of both reinforcements and concrete are employed in the pushover analyses. With this technique, highly computationally expensive and complicated dynamic analysis of multi-degree-of freedom systems (MDOF) can be converted to simple yet reliable SDOF systems while saving significant computing time.

II. METHODOLOGY

The proposed method consists of several steps as shown in Fig. 1. As the first step, pushover analysis of selected water tank is conducted using three-dimensional finite element model which consists of elements representing concrete and reinforcement bars. Then, a bilinear lateral load–lateral deformation model is established from the pushover curve. Two slopes of the bilinear model, k_1 being the initial slope and k_2 being the slope at the inelastic range are decided by fitting two straight lines to the visible two parts of the pushover curve based on the equivalent energy criterion (i.e., areas enclosed by the original curve and the two straight lines are equal), as shown in Fig. 2. The bilinear model will be used to determine required stiffness (K_{eq}) at different displacement levels in solving equation of motion of equivalent SDOF system given in (1). The equivalent mass (M_{eq}) is computed from the volume of concrete and water as appropriately for fully-filled and empty conditions. Equivalent damping (C_{eq}) is assumed to be 5%. The term $\ddot{u}_g$ is the ground accelerations of particular earthquake record and u, $\dot{u}$, and $\ddot{u}$ are the displacement, velocity and acceleration of the mass, respectively.

$$M_{eq}\ddot{u} + C_{eq}\dot{u} + K_{eq}u = -M_{eq}\ddot{u}_g \qquad (1)$$

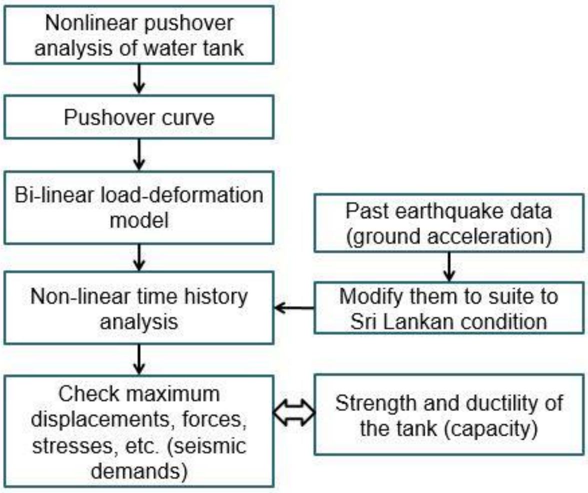

Fig. 1. Flow chart of the procedure

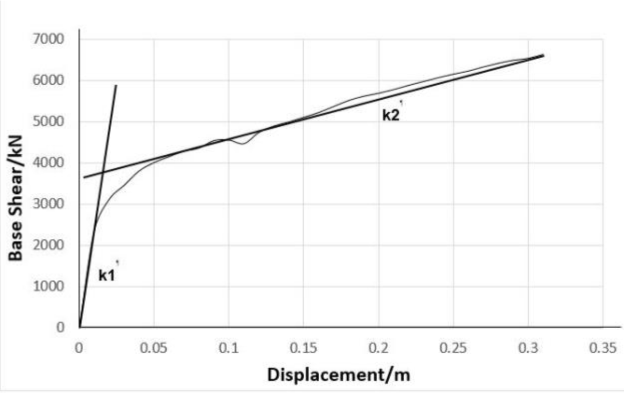

Fig. 2. Bilinear model of pushover curve

Past ground accelerations data can be downloaded from the available databases such as PEER. It is important to modify these acceleration records to suit with Sri Lanka condition. Then, the corresponding equation of motion of the equivalent nonlinear SDOF system is solved to obtain the maximum lateral displacement, base shear and other interested quantities. These quantities (demands) can be compared with the relevant capacities to check the safety of the tank.

A. *Finite Element Model*

In order to conduct nonlinear pushover analysis, finite element models are developed for the selected elevated tanks using MidasFea program [7]. Concrete segments are modelled using 8-node hexahedral elements and reinforcement bars by link elements. Two tanks of capacity 1200 m^3 and 750 m^3 that have been already constructed in Jaffna peninsula, are considered for the analysis. Element meshes of several components of the model are shown in Fig. 3. To be in the conservative side with respect to displacements, soil structure interaction was not incorporated into the analysis. As such, the base of the tank is assumed to be fixed. Two extreme cases, fully-filled and empty conditions of the tanks are considered in pushover analysis. Accordingly, the weight of the water mass is applied as point loads along the circumference of the top of the supporting cylinder. The self-weight of concrete and steel parts are incorporated to the model by assigning respective densities.

In nonlinear time history analysis, the liquid in the tank is modelled as a single mass with impulsive component of the water mass. This is a conservative assumption because the contribution of sloshing mode has been found to generate lower total response comparing to ignoring it [6].

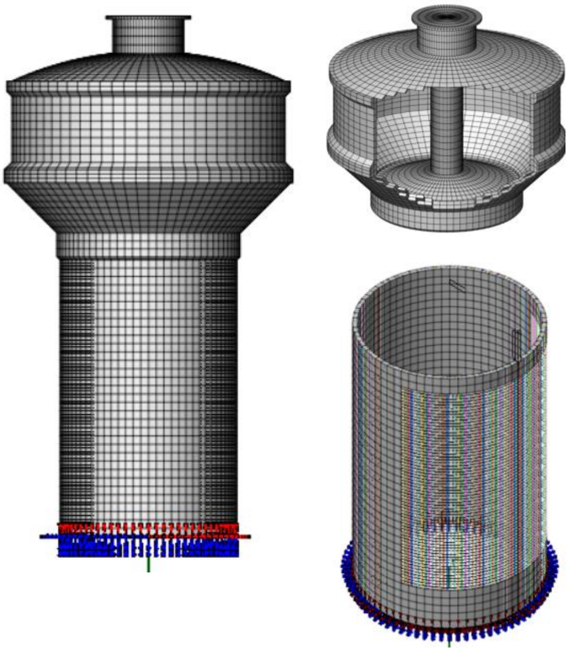

Fig. 3. Views of concrete and steel element meshes

B. *Material Models for Steel and Concrete*

Constitutive models representing the behaviour of reinforced concrete after cracking can be classified mainly into two models as discrete crack model, which is also called discontinuous model, and a smeared crack model. Furthermore, the smeared crack model can be classified basically into two models such as a decomposed-strain model and a total strain model depending on the numerical analysis methods adopted to simulate cracks. In MidasFea, the total strain crack model which is classified under the smeared crack model to predict the behaviour of reinforced concrete elements is available. In this study, total strain crack model with configuration of fixed crack model including secant stiffness, lateral crack effect and confinement effect, is used. The tension softening and compression behaviour of reinforced concrete material are represented by Hordijk and Thorenfeldt models [8]. For inelastic behaviour of steel, Von Misses yield criterion with kinematic strain hardening model is employed. The steel parameters are computed using a bilinear stress-strain curve.

C. *Modified Ground Acceleration Records*

Ground acceleration records are essential in order to conduct nonlinear dynamic analyses of the structure. There are three types of accelerograms namely; (1) Artificial accelerograms, (2) Natural accelerograms and (3) Simulated accelerograms. Analyses using simulated accelerograms are fairly complex to be implemented as they require a large number of input parameters and a comprehensive knowledge of the seismotectonic setting of the area under study. Therefore, this study uses real accelerograms for the dynamic analysis as real seismic input has the important advantage to account for amplitude, frequency content, energy content and duration characteristics of the real ground shaking. The above dynamic characteristics are very important in the assessment of nonlinear response of structures. The original time histories are scaled to match with the reference response spectrum of return period of 475 years proposed by Uduweriya et al. [9]. As per [9], the Peak Ground Acceleration (PGA) across Sri Lanka is in the range of 0.05–0.1g for the 475-year return period event and in the range of 0.07–0.3g for 2475-year return period event. In order to set PGA at 0.1g, the 475-year return period was selected in this study to predict the displacement demands.

III. RESULTS

A. *Nonlinear Pushover Analysis*

Tanks with two capacities, 1200m^3 and 750m^3, each having three different heights (21.425 m, 16.425 m, 11.425 m) were considered in the analysis. The geometry and the dimensions of the tanks are as per the construction drawings of the tanks. For each height, six cases having six longitudinal reinforcement ratios, as presented in Tab. 1 and Tab. 2, were used. It should be stated that reinforcement ratios of 0.318 (Tab. 1) and 0.309 (Tab. 2) are corresponding to 10 mm bar size as per the original design values for 1200m^3 and 750m^3 tanks, respectively. The rest of the ratios are corresponding to bar diameters of 12, 14, 16, 18 and 20 mm. These bar diameters were decided by gradually increasing the design value of 10 mm bar diameter in order to check the effect of reinforcement ratio on the pushover curve and on the displacement, demands. As a result, there were 36 three dimensional finite element models created using MidasFea for each of fully-filled and empty tank conditions. Thus, altogether 72 pushover analyses were conducted and the corresponding bilinear load-displacement models were developed. These bilinear models were then used in time history analysis of equivalent SDOF systems.

TABLE I. DETAILS OF 1200M^3 TANK MODELS

Model No	**Shaft Height/m**	**Tank Diameter/m**	**Longitudinal R/F Ratio**
A1	21.425	16.5	0.318
A2			0.458
A3			0.623
A4			0.814
A5			1.030
A6			1.272
A7	16.425	16.5	0.318
A8			0.458
A9			0.623
A10			0.814
A11			1.030
A12			1.272
A13	11.425	16.5	0.318
A14			0.458
A15			0.623
A16			0.814
A17			1.030
A18			1.272

TABLE II. DETAILS OF 750M^3 TANK MODELS

Model No	Shaft Height/m	Tank Diameter/m	Longitudinal R/F Ratio
B1	21.425	14.9	0.309
B2			0.445
B3			0.606
B4			0.792
B5			1.002
B6			1.237
B7	16.425	14.9	0.309
B8			0.445
B9			0.606
B10			0.792
B11			1.002
B12			1.237
B13	11.425	14.9	0.309
B14			0.445
B15			0.606
B16			0.792
B17			1.002
B18			1.237

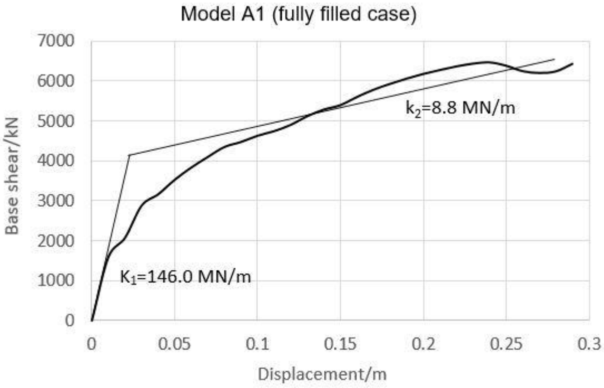

Fig. 4. Pushover curve and bilinear approximation for model A1 (fully-filled condition)

Tab. 3 and 4 contain k_1 and k_2 values obtained for 1200m^3 and 750m^3 tanks under fully-filled conditions. Results were obtained for empty conditions as well.

TABLE III. STIFFNESS VALUES OF FULLY-FILLED 1200M^3 TANKS

Model No	k_1 kN/m	k_2 kN/m
A1	146,786	8,836
A2	167,143	10,950
A3	202,727	7,383
A4	227,083	7,422
A5	244,074	7,103
A6	286,400	8,382
A7	182,951	12,015
A8	242,632	11,066
A9	285,476	9,844
A10	358,462	9,259
A11	417,714	12,961
A12	488,333	12,013
A13	259,504	20,679
A14	316,923	11,136
A15	380,905	10,009
A16	434,634	8,650
A17	498,020	6,488
A18	556,190	7,471

TABLE IV. STIFFNESS VALUES OF FULLY-FILLED 750M^3 TANKS

Model No	k_1 kN/m	k_2 kN/m
B1	73,453	5,152
B2	138,333	8,152
B3	191,111	7,629
B4	219,750	6,022
B5	260,302	6,234
B6	294,762	6,402
B7	124,722	9,304
B8	210,278	9,777
B9	261,667	8,382
B10	321,143	8,265
B11	356,865	7,947
B12	393,716	9,888
B13	179,464	17,509
B14	270,885	9,425
B15	328,684	8,419
B16	397,872	8,429
B17	466,944	9,146
B18	520,225	9,232

B. Non-linear Time History Analysis

For nonlinear time history analyses, one horizontal components of seven earthquake records, namely (1) Cape Medecino-1992, (2) Chi-Chi-1999, (3) Friuli Forgaria-1976, (4) Kobe-1995, (5) Colinga USA-1994, (6) Palm Springs-1986, and (7) Cocaeli Italy-1999, downloaded from PEER database, were considered. First, the acceleration values of each record were modified to match with Sri Lankan condition based on response spectrum proposed by Uduweriya et al. [9]. Then, averaged accelerations of these seven earthquakes were used in the analyses. Both water mass and tank mass were considered for fully filled condition while only tank mass was considered for empty tank condition. Maximum displacements obtained from the analyses are listed in Tab. 5 and Tab. 6, respectively for 1200m^3 and 750m^3 tanks.

TABLE V. DISPLACEMENT DEMANDS OF 1200M^3 TANKS

R/F ratio	Displacement/mm (Empty Tank)		
	h=21.425 m	h=16.425 m	h=11.425 m
0.318	579	353	238
0.458	540	377	234
0.814	425	211	104
1.272	311	112	62
	Displacement/mm (Fully-Filled Tank)		
0.318	532	329	220
0.458	513	269	232
0.814	426	199	106
1.272	298	105	61

TABLE VI. DISPLACEMENT DEMANDS OF 750M^3 TANKS

R/F ratio	Displacement/mm (Empty Tank)		
	h=21.425 m	h=16.425 m	h=11.425 m
0.309	610	414	247
0.445	563	398	236
0.792	413	239	93
1.237	270	137	59
	Displacement/mm (Fully-Filled Tank)		
0.309	570	385	239
0.445	516	366	214
0.792	388	222	89
1.237	248	129	62

The variation of maximum displacement with reinforcement ratios for 1200m^3 and 750m^3 tanks under fully-filled and empty conditions are shown in Figs. 5 to 8. It is clear from these figures that when reinforcement ratio increases the displacement demand decreases linearly. The rate of decrease is much higher in empty tank condition than the fully-filled condition.

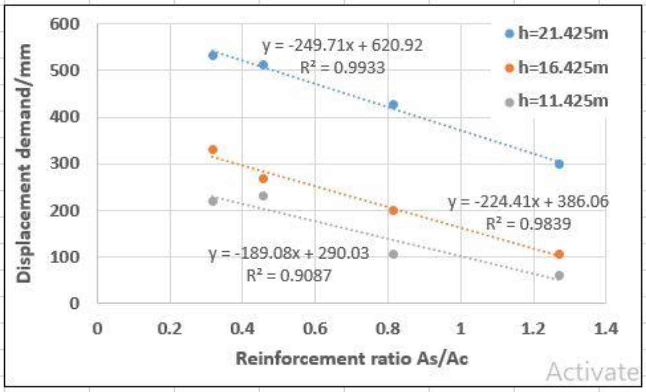

Fig. 5. Displacements vs reinforcement ratio of 1200m^3 tank (fully-filled)

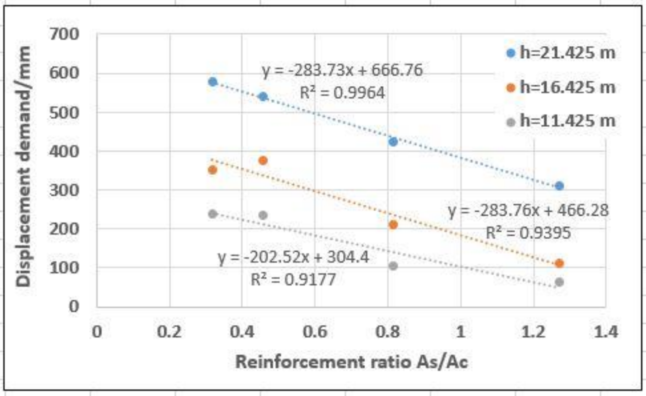

Fig. 6. Displacement vs reinforcement ratio of 1200m^3 tank (empty)

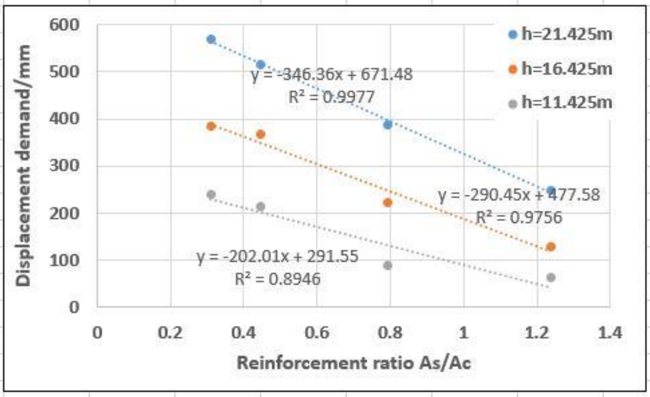

Fig. 7. Displacement vs reinforcement ratio of 750m^3 tank (fully-filled)

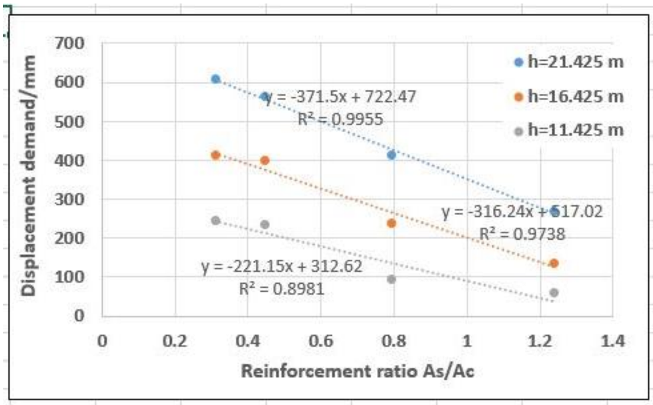

Fig. 8. Displacement vs reinforcement ratio of 750m^3 tank (empty)

IV. CONCLUSION

In this study, two capacities of tanks (1200m^3 and 750m^3), three cases of tank stem heights (21.425m, 16.425m, and 11.425m), six types of longitudinal reinforcement ratios, and two tanks conditions (fully-filled and empty tanks) were considered as variables in the analysis. Pushover analyses of 72 cases of elevated Intze type concrete water tanks were carried out using three-dimensional finite element models incorporating both steel and concrete nonlinear material behaviour. Using the pushover curve, bilinear load deformation models for each case was obtained and was used in nonlinear time history analyses using equivalent single degree of freedom sustems. The following can be drawn as the conclusions of this study;

(1) The proposed time history analysis procedure was found to be very computational efficient because it reduces a large number of degree of freedoms associated with three-dimensional modelling into an equivalent single degree of freedom system.

(2) The nonlinear lateral load-displacement behavior of elevated water tanks can be effectively incorporated into the SDOF system through the proposed bilinear load deformation models.

(3) When longitudinal reinforcement ratio (i.e., bar diameter with constant spacing) increases the displacement demand decreases linearly.

(4) The decrease of displacement demand is higher when the tank is under empty condition compared to fully- filled conditions.

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