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Direct Displacement Based Design of Reinforced Concrete Elevated Water Tanks Frame Staging

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ABSTRACT

Elevated water tanks supported by the reinforced concrete (RC) Staging are classified as inverted pendulum structures. These are considered as structures of high post-earthquake importance and should remain functional after the seismic events. National codes of various countries recommend Force-Based Design (FBD) procedure for water tank staging, which does not ensure nonlinear performance level for a given hazard. Therefore, it becomes necessary to design these structures with a performance-based design approach like Direct Displacement-Based Design (DDBD). Many design engineers consider that the behavior of frame staging of the elevated water tank is similar to the building's frame and generally adopt the same design principles for both types of structures. However, the seismic behavior of the building frame is significantly different from frame staging due to the absence of diaphragm action at the bracing level and concentrated mass at the top level only. Therefore, it may not be rational to utilize the same DDBD procedure of the building's frame for the design of frame staging of the elevated water tanks. The present study proposes some modification in existing DDBD procedure (used for the design of frame building) based on the nonlinear time history analysis of twenty meters high RC frame staging with four different configurations. The modifications are proposed in terms of inelastic displacement profile, design displacement, effective height, and effective mass calculation. Further, the performance of the same RC frame staging designed using the proposed DDBD procedure has been assessed using nonlinear static and dynamic analyses to verify the suitability of proposed modifications.

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1. INTRODUCTION

In highly populated countries like India, the most economical method for water distribution is to use a combined pumping and gravity system. In this method, the water is stored in large overhead water tanks by pumping and distributed by means of gravity (Figure 1(a)). Even moderate damage to water tanks can make it non-functional leading to additional chaotic condition after an earthquake. Therefore, water tanks are categorized as lifeline structures that must be designed to withstand the seismic forces with minimal damage and remain functional even after a major seismic event. Generally, elevated water tanks are classified based on support conditions, construction materials, and capacity. Nowadays, construction of tall RC water tanks on frame staging has become a common structure in rural and urban India. Similarly, this type of water tanks is also popular in many countries viz. Iran [1-2], New Zealand [3], Chile [4] and Turkey [5]. These structures are classified as small, medium, large and very large water tanks based on their capacities [6].

It has been evidenced from past earthquakes that several elevated water tanks were significantly damaged or failed due to ground shaking [7-14]. The elevated water tank provides potable water and water to subdue building fires, which failure of them may lead to inconvenience in post-earthquake life functioning's. Moreover, the failure of water tanks during an earthquake would lead to a catastrophe and loss of human lives and properties. In order to mitigate these post-earthquake consequences, it is essential to ensure the safety of water tanks against seismic loads to remain serviceable even after these events. Therefore, various Indian national

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design codes and guidelines recommend considering water tanks as an important structure [15-23].

The contemporary design practice of water tanks uses Force Based Design (FBD) approach. Many countries have framed their national codes for design of water tanks by FBD approach [23]. As earthquakes are infrequent events, and may or may not come during the service life of a structure hence, FBD approach allows considering a reduced level of anticipated design forces by considering parameters like over strength, redundancy and ductility of structure [21-26]. The uncertainties involved in these inherent parameters make a prediction of the inelastic performance of these structures difficult. Therefore, it is essential to adopt a seismic performance-based approach in the design of the elevated water tank structure. Direct Displacement-Based Design (DDBD) approach is a relatively new performance-based design method having well-established procedure for frame building structures and claims that structure designed by DDBD will perform in an anticipated manner during seismic events [27-37].

2. DDBD PROCEDURE FOR RC FRAME STAGING

Many researchers (Moehle [27], Kowalsky et al. [28], Priestley and Kowalsky [29], Medhekar and Kennedy [30], Pettinga and Priestley [31], Priestley et al. [32], Massena et al. [33], Moghim and Saadatpour [34], Dzakic et al. [35], Fakhraddini and Salajegheh [36] and Muljati et al. [37]) worked on DDBD procedure to obtain realistic approximation of base shear and its distribution for RC bridges and building frames. To predict the inelastic displacement of structure Moehle [27] proposed an iterative procedure which calculates the displacement demand and capacity of structure based on it's strength and stiffness using displacement spectra. This procedure is an iterative procedure in which strength and stiffness of structure are variables. Therefore, Kowalsky et al. [28] proposed a displacement-based method for 'SDOF' system like single pier RC bridge system of known mass to predict required stiffness of structure for desired displacement, based on correlation between displacement ductility, effective damping and displacement spectra (for respective effective damping). Further, Priestley and Kowalsky [29] adopted the same approach for multi degree of freedom system. In the detailed procedure proposed by Priestley et al. [32], design story displacements of RC frame building is calculated using normalized inelastic mode shape and the displacement of critical story. Two different expressions have been proposed to predict normalized inelastic mode shape i.e. linear profile for building up to four-story and parabolic profile for taller buildings which are based on the dynamic behavior of RC frames [38]. The procedure makes use of substitute single-degree-of-freedom (SDOF) system instead of actual multi-degree-of-freedom (MDOF) system using design story displacements [30]. It shall be noted that the equations for normalized inelastic mode shape and the displacement of the critical story which is considered as bottom story of RC frame buildings can not be applied directly to other structures such as elevated water tank staging since its dynamic behavior and hinging patterns are different from RC building frames [39]. Moreover, in case of building frame, the equivalent viscous damping is computed using displacement ductility of structure [39]. In general for normal building frame, the inelastic displacement is leading to higher damping, whereas, elevated water tank being a lifeline structure the allowable damage is limited thus the damping will be lower.

Lakhade et al. [39] stated that, elevated water tank frame staging is apparently similar to building frame but their mass and stiffness distribution is significantly different. In building frames, loads are distributed at each story level whereas, in tank staging entire load is concentrated at the top. Further, in building frame slab at each story level provides diaphragm action which is missing in frame staging. From the comparative study of building frame and frame staging, they concluded that the building frame has higher base shear capacity than that of frame staging, and frame staging has a cantilever displacement profile. It should be noted that since the behavior of building frame and frame staging are significantly different from each other; hence, prevalent DDBD approach for building frame cannot be directly used for the design of frame staging, without appropriate modifications. As mentioned earlier various studies have been conducted on RC building frame [27-37] with some modifications in existing DDBD procedure (viz. inelastic normalized mode shape consideration, equivalent viscous damping consideration, etc.) for better approximation of design forces based on nonlinear time history analysis results.

The objective of the present study is to propose modification(s) in prevalent DDBD approach for building frame based on the nonlinear time history analysis of RC frame staging, which can be used for the design of RC water tank frame staging. A comparative study of the nonlinear performance of RC frame staging designed using prevalent Indian national design codes and the DDBD approach with proposed modification has been performed.

In DDBD procedure, the structure is designed using equivalent single-degree-of-freedom (SDOF) representation of the real structure considering desired inelastic displacement response, rather than by its initial elastic characteristics [30]. In this approach, the secant stiffness 'K_e' at maximum displacement 'Δ_d' and equivalent viscous damping representative of combined elastic damping and hysteretic energy absorbed during inelastic response are used to characterize the structural behavior. The characteristic design displacement (Δ_d) of the substitute structure (SDOF) depends on the limit state deformation of the most critical member of the real structure, and the target displacement profile of the structure. The DDBD formulation prescribed by Priestley *et al.* [32] has been used in the present study. Details of the proposed modifications for DDBD of elevated water tank is presented in following paragraphs.

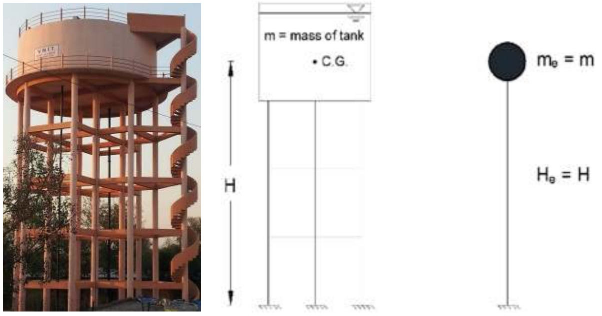
Elevated water tanks are like inverted pendulum structures whose most of the mass is concentrated on the top of tank staging, therefore, the tank itself has been assumed as SDOF system (as shown in Figure 1). Pettinga and Priestley [31] modified the design displacement profile for buildings with more than four-story to meet the actual inelastic displacement profile observed from time history analysis. Therefore, to understand the displacement behavior of the frame staging, preliminary nonlinear time history analysis has been performed on force-based designed RC frame staging. Based on the obtained inelastic story displacement profile, a generalized trendline equation have been developed (Equation (1)).

The normalized inelastic mode shape equation for the frame staging has been developed based on the relationship between normalized inelastic story displacement 'δ_i', the height of bracing level 'h_i' and the total height of staging 'h_n'.

$$\delta_i = \left(\frac{11}{20}.\frac{h_i}{h_n}\right) + \left(\frac{4}{3}.\left(\frac{h_i}{h_n}\right)^2\right) - \left(\frac{7}{8}.\left(\frac{h_i}{h_n}\right)^3\right) \tag{1}$$

The displacement behavior of frame in global failure mechanism mainly governs by the rotational capacity of the beam at the critical story [29]. The yield rotation capacity of beam 'θ_y' has been determined using an equation proposed by Priestley et al. [29] (Equation (2)).

$$\theta_y = 0.5 \times \varepsilon_y \times \left(\frac{L}{D_b}\right) \tag{2}$$



(a) (b)

Figure 1. (a) Elevated water tank on RC frame structure (b) Equivalent SDOF representation of elevated water tank on frame staging

where 'ε_y' is the yield strain of reinforcing steel, 'L' is the length of the beam and 'D_b' is the depth of the beam. The yield displacement of an equivalent SDOF system has been calculated based on yield rotation capacity of bracing beam 'θ_y' and the height of the equivalent SDOF system 'H_e' (Equation (3)).

$$\Delta_y = H_e \cdot \theta_y \tag{3}$$

The design story displacements 'Δ_i' is calculated using the shape vector 'δ_i' scaled with respect to the critical story displacement 'Δ_c' and to the corresponding mode shape at the critical story level 'δ_c'(equation 4). The inter-story drift obtained from preliminary time history analysis of FBD tank staging shows that in case of frame staging, inter-story drifts are maximum at mid-level of tank staging. Hence, the middle staging level is considered as a critical story and design displacement profile has been calculated using Equation (4).

$$\Delta_i = \delta_i .(\frac{\Delta_c}{\delta_c}) \tag{4}$$

Various studies [28-33, 36] provide relationship for conservative estimation of equivalent viscous damping based on ductility 'μ'. The displacement ductility (μ) of the equivalent SDOF system has been determined based on its design displacement at top of staging 'Δ_d' and the yield displacement 'Δ_y' (Equation (5)).

$$\mu = \frac{\Delta_d}{\Delta_y} \tag{5}$$

As liquid storage tanks are categorized as important structure and should remain functional even after the seismic events. Therefore, it is proposed to design tank staging for 5% damping, which means ductility of frame staging requires to be one. Figure 2 shows the design displacement spectra for 5% damping for hard soil [20]. The effective period 'T_e' of the equivalent SDOF system at maximum displacement response measured at the effective height 'H_e' can be read from the displacement spectra.

The effective stiffness 'K_e' of the equivalent SDOF system at maximum displacement is thus obtained by Equation (6) using effective period of equivalent SDOF

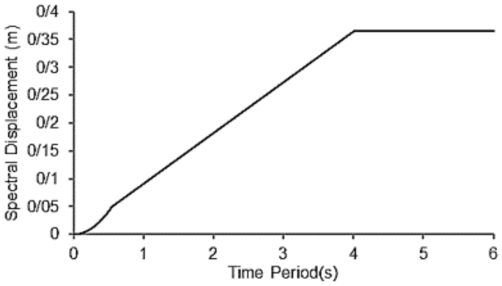


Figure 2. Design displacement spectra for 5% damping

system 'T_e', and the total mass of tank 'm_e'.

$$K_e = \frac{4\pi^2 m_e}{T_e^2} \tag{6}$$

The design base shear force, 'F' is consequently can be estimated based on 'K_e' and 'Δ_d' of the equivalent SDOF system (Equation (7)).

$$F = K_e \cdot \Delta_d \tag{7}$$

3. DESIGN DETAILS OF THE INVESTIGATED TANKS

In the present study, four twenty-meter height frame staging tanks with capacities of 0.09 Megaliters (Ml), 0.6 Ml, 1.7 Ml and 2.6 Ml representing small, medium, large and very large tanks, respectively have been considered. The tank dimensions, columns configuration, and sizes are considered as per Lakhade *et al.* [26] and shown in Figure 3. The tanks are assumed to be situated on medium soil strata and located in the highest seismic zone of India (zone V) with peak ground acceleration as 0.36g as per the part 1 of IS 1893:2016. The reinforced concrete frames are made using concrete with nominal characteristic compressive strength of 30 MPa (M30) and the reinforcing steel having yield strength of 415 MPa (HYSD 415). In FBD approach, the frame staging is designed as a special moment resisting frame with a response reduction factor of 4. Various pre-standards/guidelines like FEMA 356 and ASCE 41-10 defined 1% maximum inter-story drift as immediate occupancy performance level [40, 41]. Hence, in the present study, frame stagings are designed for 1% target drift. Based on the base shear calculation by FBD and DDBD proportioning of the section sizes and reinforcement in the structural members has been assigned. Limit state member design procedure of IS 456:2000 has been used for designing the members. In FBD approach, to attend desired global mechanism of the frame under seismic loading, special ductility provisions of IS 13920: 2016 has been adopted in the design, and in case of DDBD approach, the capacity design approach proposed by Priestley et al. [32] has been used. In FBD frame, it has been ensured that sum of column nominal design strength meeting at the joint will be 1.4 times more than that of the sum of beam nominal design strength of meeting at that joint. The effective stiffness of cracked structural elements has been considered as per Kumar and Singh [42]. Part 1 of IS 1893 [21] has been used in seismic load calculation in FBD.

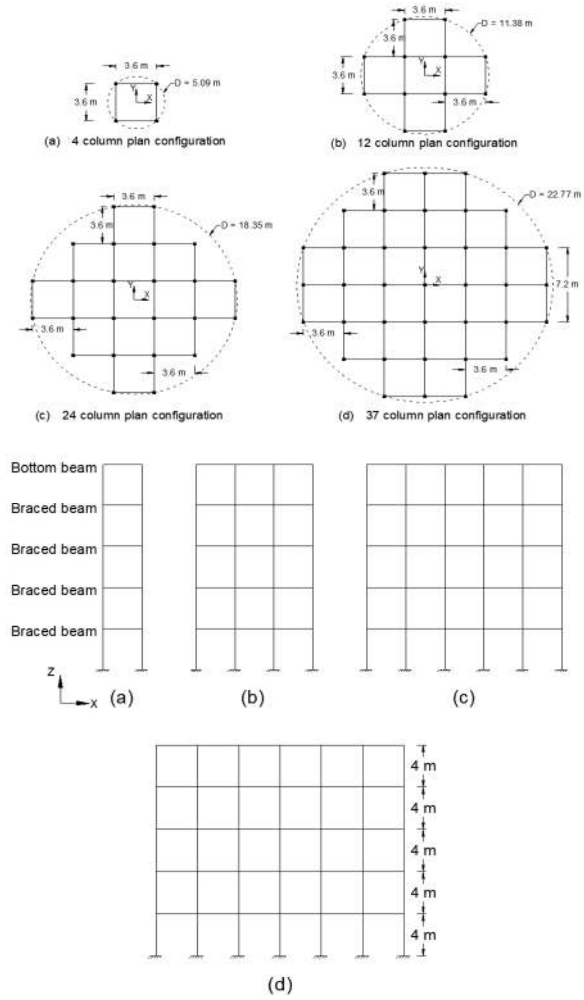


Figure 3. Staging plan configuration and elevation details of (a) small, (b) medium, (c) large and (d) very large tanks

4. DESIGN DETAIL OF RC FRAME STAGING of TANK

The member sizes and reinforcement details of all the 4 tanks by both FBD and DDBD approaches are given in Table 1. The FBD tanks are designed by IS 456:2000 and IS 13920:2016, whereas DDBD tanks are designed by capacity design approach proposed by Priestley *et al.* [32]. Significant change can be observed in the reinforcement and section sizes of column of FBD and DDBD staging. DDBD approach makes column relatively stronger than that of FBD approach. Further the DDBD approach estimates relatively higher reinforcement in frame staging.

5. NONLINEAR ANALYSIS

Nonlinear (NL) analysis including NL static and NL dynamic analyses have been performed for all the aforementioned tank models as per the guidelines of ASCE 41 [43]. In nonlinear static procedure (NSP) i.e. pushover analysis, the magnitude of the structural displacement in lateral direction is incrementally increased in accordance with a certain predefined pattern.

TABLE 1. Design details of RC frame staging of tanks

Tank capacity	Design approach	Member	Width (mm)	Depth (mm)	Reinforcement details
Small (0.09 Ml)	FBD	Bottom Beam	300	450	5 # 20 Φ (top) + 4 # 20 Φ (bottom)
		Braced Beam	250	450	3 # 20 Φ (top) + 3 # 20 Φ (bottom)
		Column	450	450	12 # 25 Φ*
	DDBD	Bottom Beam	350	450	4 # 20 Φ (top) + 4 # 20 Φ (bottom)
		Braced Beam	300	450	4 # 25 Φ (top) + 4 # 25 Φ (bottom)
		Column	450	400	14 # 20 Φ
Medium (0.6 Ml)	FBD	Bottom Beam	350	700	5 # 25 Φ (top) + 4 # 25 Φ (bottom)
		Braced Beam	300	550	4 # 25 Φ (top) + 3 # 25 Φ (bottom)
		Column	500	500	12 # 25 Φ
	DDBD	Bottom Beam	350	600	5 # 20 Φ (top) + 4 # 20 Φ (bottom)
		Braced Beam	350	500	5 # 25 Φ (top) + 5 # 25 Φ (bottom)
		Column	550	500	12 # 25 Φ
Large (1.7 Ml)	FBD	Bottom Beam	400	700	5 # 25 Φ (top) + 4 # 25 Φ (bottom)
		Braced Beam	300	550	4 # 25 Φ (top) + 3 # 25 Φ (bottom)
		Column	500	500	14 # 25 Φ
	DDBD	Bottom Beam	400	700	5 # 20 Φ (top) + 4 # 20 Φ (bottom)
		Braced Beam	300	550	5 # 25 Φ (top) + 5 # 25 Φ (bottom)
		Column	575	550	14 # 25 Φ
Very large (2.6 Ml)	FBD	Bottom Beam	400	650	5 # 25 Φ (top) + 3 # 25 Φ (bottom)
		Br aced Beam	300	500	5 # 20 Φ (top) + 4 # 20 Φ (bottom)
		Column	500	500	12 # 25 Φ
	DDBD	Bottom Beam	400	650	4 # 20 Φ (top) + 3 # 20 Φ (bottom)
		Braced Beam	300	500	4 # 25 Φ (top) + 4 # 25 Φ (bottom)
		Column	600	550	14 # 25 Φ

** 12 # 25 Φ – 12 number of HYSD 25 mm diameter bars, Ml- Megaliters*

Pushover analysis gives better insight of the weak link inside the structural frame under monotonic lateral loading. Further, to assess the actual behavior of frame staging in seismic events, nonlinear dynamic analysis i.e. time history analysis has been performed for the same models. NL time history exhibits cyclic loading and load reversal; hence the results may be affected by type of hysteretic behavior (viz. process of energy dissipation through deformation of structural member) [44]. Lumped plastic hinge model as per ASCE 41 [43] has been used to simulate the nonlinear behavior of members. In case of beam members, uncoupled moment hinges (M3 hinge) and for column members, coupled axial force and biaxial bending moment hinges (P-M2-M3 hinge), have been assigned at both ends. Takeda Hysteresis model has been used for simulating the degrading hysteretic behavior of reinforced concrete in nonlinear analysis (Takeda et al. [46]). This popular hysteric model is very appropriate for reinforced concrete [44]. Figure 4 shows moment-rotation behavior of a middle level bracing of medium capacity tank designed as per DDBD approach corresponding to time history record TH-9.

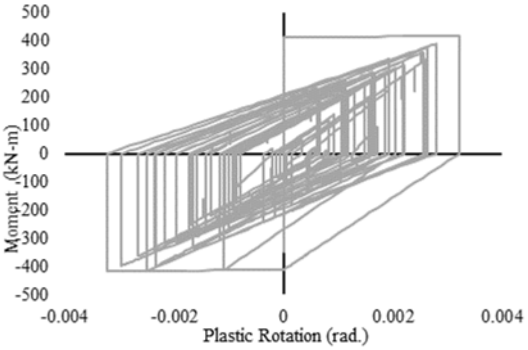
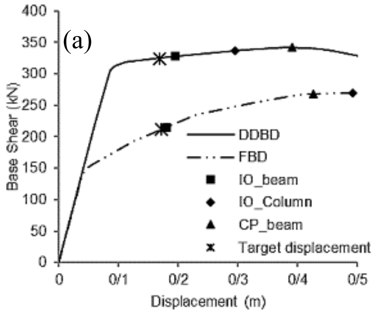


Figure 4. Moment-rotation behavior of a bracing

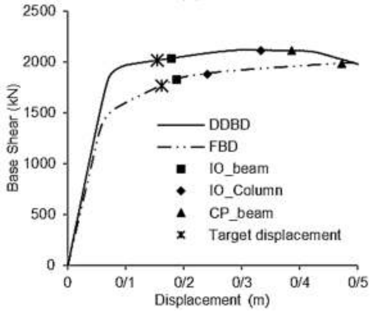
The direct integration method has been adopted for the time history analysis. All the above-mentioned analysis has been performed using structural analysis software SAP2000. The results of the nonlinear analyses have been discussed in the following section.

5. 1. Nonlinear Static Analysis Results

The nonlinear static pushover analysis has been performed on all eight-tank models (four tanks designed using FBD and four tanks designed using DDBD approach) and capacity curves i.e. roof displacement vs. base shear have been obtained (Figure 5). Further, these capacity curves are bi-linearized as per the procedure prescribed by the ASCE 41 [40]. The results of yield displacement, yield base shear, target displacement and the ratio of yield base shear to design base shear are summarised in Table 2. As mentioned earlier, the frame staging members size designed using DDBD approach are comparatively higher than that of FBD frame staging and hence DDBD frame staging results into relatively higher initial stiffness.



(a)



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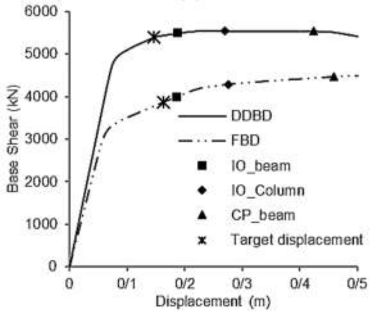

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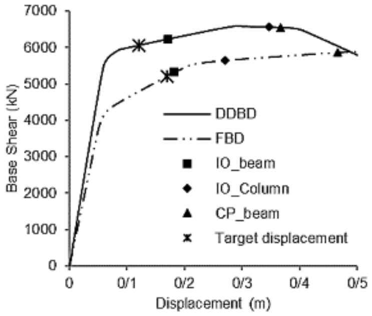


(d)

Figure 5. Capacity curves of (a) small, (b) medium, (c) large and (d) very large tank frame stagings

TABLE 2. Capacity curve results

Tank	Design Approach	Yield Base Shear (kN)	Yield Displacement (mm)	Design Base Shear (kN)	The Ratio of Yield Base Shear to Design Base
Small (0.09 Ml)	FBD	195	55.3	114*	1.711
	DDBD	318	87.6	228	1.395
Medium (0.6 Ml)	FBD	1726	71.4	637.5*	2.707
	DDBD	1944	71.8	1164	1.670
Large (1.7 Ml)	FBD	3798	71.9	1396.5*	2.720
	DDBD	5124	78.4	3096	1.655
Very large (2.6 Ml)	FBD	5026	66.5	1977*	2.542
	DDBD	6588	67.2	4635	1.421

* design base shear calculated using partial load factor (γ) as 1.5 as per IS 1893 (1) [18]

During pushover analysis, it was observed that hinge formation starts in middle-level bracing beams of frame staging designed using force-based approach and then hinges formation progress in lower level bracing beams. Later hinge formation was observed in upper-level braces and in few columns subjected to tensile forces at foundation level. Whereas, in direct displacement-based designed frame staging the hinge formation starts from top braces, then hinges formation progresses in lower level bracing beams and later form in few columns subjected to tensile forces at foundation level. These alterations in hinge formation highlight the uniform distribution of ductility over the height of frame staging designed using DDBD approach. The bi-linearization of capacity curves of medium, large and very large tanks shows that in DDBD frame staging global yielding observed at 10 to 25% higher base shear, and 6 to 10% higher displacement. DDBD approach significantly enhances the performance of small capacity tank with slender frame staging which globally yields at 40% higher base shear and 35% higher displacement than that of FBD approach. The ratio of yield base shear to design base shear is relatively smaller in case of DDBD approach than that of FBD approach, which demonstrates that DDBD approach gives better control over the desired performance of frame staging in terms of strength/capacity. In FBD frame staging target displacements are very close to immediate occupancy performance limit.

5. 2. Nonlinear Dynamic Analysis Results

To assess the performance of all eight tanks designed using FBD and DDBD approaches (four models each) in an anticipated seismic event, nonlinear time history analyses have been performed.

5. 2. 1. Selection of Strong Ground Motion Records

Earthquake strong ground motions are random in nature and significant record-to-record variability can be observed. Large variability in records representing a scenario and their non-smoothed response spectra makes a selection of ground motion records matching to the target spectral shape very difficult. To overcome this limitation, various approaches like 'wavelet transformation' has been developed to manipulate the real ground motion record either in the time or frequency domain. Various national codes like EC-8 allow the use of code compatible acceleration records for time history analysis [45]. Various DDBD related studies used spectrum compatible ground motion records for performance assessment [27, 29-33, 47]. Mukherjee and Gupta [48] developed a wavelet-based tool WAVGEN to modify a recorded accelerogram so that it becomes compatible with a target spectrum and has been used in the present study. Guidelines provided by FEMA 356, EC-8, ASCE 7, FEMA 368, and NZS 1170.5 [40, 45, 49, 50, 51] states that:

- minimum of three ground motions shall be used for analysis;
- if less than seven ground motions are considered then the maximum response shall be considered.

However, as ASCE 7 [52] minimum of eleven-time history records shall be used for nonlinear performance assessment. In the present study, an array of twelve ground motion records compatible to IS 1893(1) [21] on hard soil spectrum with PGA value 0.36g has been used. The details and response spectrum of selected twelve compatible ground motion are depicted in Figure 6 and Table 3, respectively.

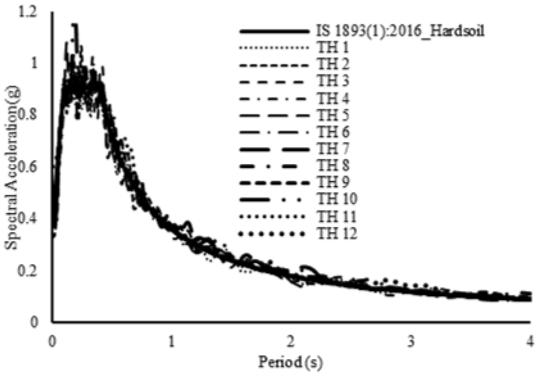


Figure 6. The response spectrum of selected twelve ground motions compatible to IS 1893(1) [18] spectrum for hard soil

TABLE 3. Summary of Earthquake events, site and source data (PEER NGA West [50])

ID No	Earthquake			Site Data		Source (Fault type)
	M	Year	Name	Site class	Vs_30 (m/sec)	
TH-1	7.6	1999	Chi-Chi, Taiwan	D	259	Thrust
TH-2	6.5	1979	Imperial valley	D	196	Strike-slip
TH-3	7.1	1999	Duzce, Turkey	D	276	Strike-slip
TH-4	7.5	1999	Kocaeli, Turkey	D	276	Strike-slip
TH-5	7.3	1992	Landers	D	271	Strike-slip
TH-6	6.7	1994	Northridge	D	356	Thrust
TH-7	5.8	1937	Humbolt Bay	D	219	Strike-slip
TH-8	6.5	1942	Borrego	D	213	Strike-slip
TH-9	7.4	1952	Kern County	D	316	Reverse
TH-10	5.3	1954	Central Calif-01	D	199	Strike-slip
TH-11	6.2	1966	Parkfield	D	257	Strike-slip
TH-12	5.3	1970	Lytle Creek	D	302	Reverse

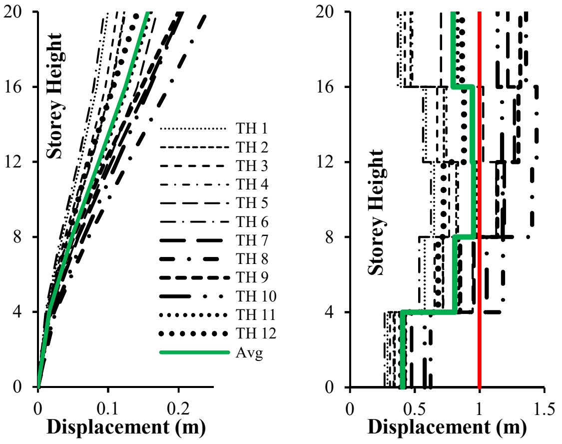
5. 2 2. Nonlinear Time History Analysis Results

As mentioned earlier, the behavior of building frame and frame staging are completely different. At this stage, nonlinear time history analysis has been performed to assess the behavior of different configurations of all four different capacity tank frame stagings designed using prevalent code based FBD approach. Various studies focus on a displacement-based approach for analysis of the seismic behavior of building structures in seismically active and near-fault regions [54], precast concrete building structures located in earthquake-prone regions [55] and monumental buildings [56]. Further, they consider relative displacements obtained in nonlinear time history analysis as indicator of damage. Therefore, in present study, the comparative assessment of global as well as local damage has been done based on maximum inter-story drift ratio.

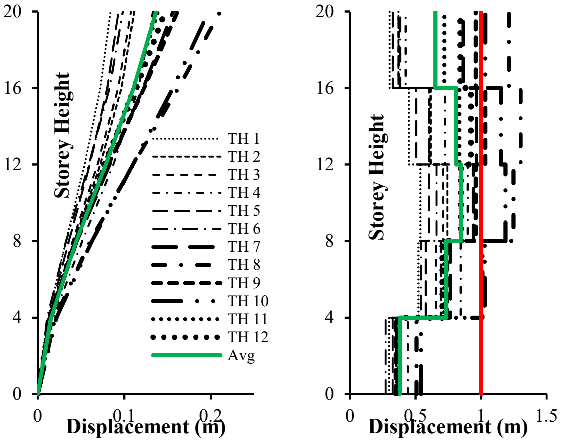
Based on the obtained displacement profile, the existing linear characteristic displacement profile equation has been altered to match the displacement profile observed in FBD tank staging (Equation (1)). Obtained inelastic displacement profile (shown in Figure 7 with red line) of all four tank frame stagings designed as per modified DDBD approach shows good agreement with the proposed characteristic displacement profile.

Further, a comparative assessment has been done based on the inelastic displacement profile and relative displacement (i.e. inter-story drift ratio) as shown in Figures 7 and 8. The maximum inelastic displacement profiles observed in FBD frame stagings are about (5 to 50) % higher than that of DDBD frame stagings. In case of medium capacity tank staging designed using FBD and DDBD approach, the difference between maximum displacements is relatively low. Further, in FBD tank staging, substantial variability has been observed in displacement profile obtained from all twelve-time history records, which is not evidenced in DDBD frame stagings. Significantly, higher displacement at the top of small capacity slender frame staging shows that FBD approach is inadequate to prevent large displacement in flexible staging. On the other hand, controlled displacement in same capacity slender staging designed using DDBD approach shows that DDBD approach overcomes this limitation.

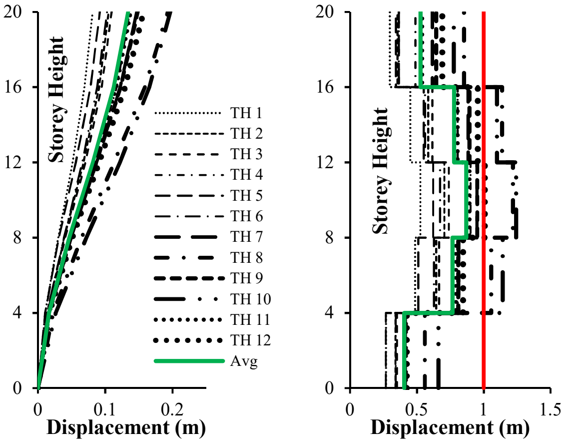
To understand the local relative displacement behavior and damage in tank staging, comparative assessment of inter-story drifts observed in FBD and DDBD frame staging's have been done. The inter-story drift results show that in case of the elevated water tank on frame staging have maximum inter-story drift at a middle level which also endorses the assumption of the middle level of frame staging as a critical story. In case of FBD frame staging of small and very large capacity tank, the maximum inter-story drift exceeds the 1% drift limit for twelve-time history records. Whereas, same staging designed using proposed DDBD approach the maximum inter-story drift exceeds the 1% drift limit only for three-time history records. Moreover, in case of FBD staging of large and medium capacity tanks the maximum inter-story drift exceeds the 1% drift limit for four-time history records. However, those staging are designed using proposed DDBD approach shows relatively better performance and less variability in the displacement profile. Overall time history analysis results indicate that proposed DDBD approach not only gives good control over the design strength but also controls the relative displacement in a better manner (Figures 6 and 7).



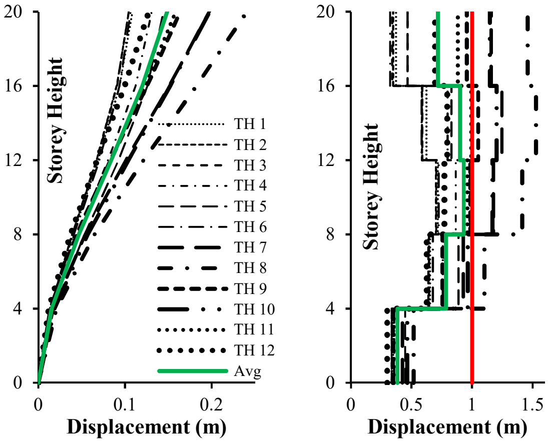
(a) Small Tank



(b) Medium Tank

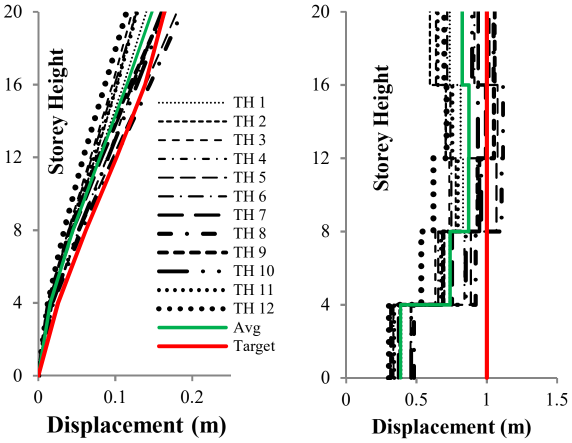


(c) Large Tank

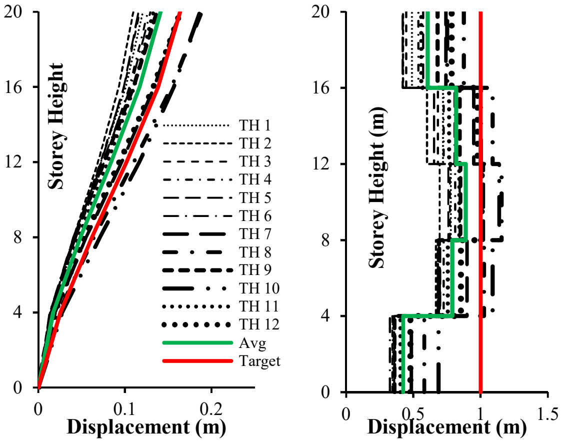


(d) Very Large Tank

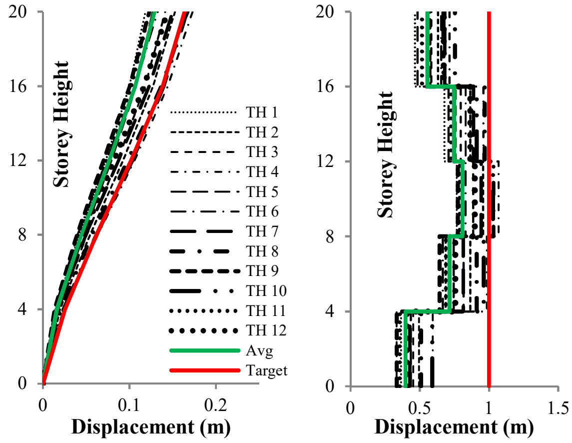
Figure 7. Inelastic displacement profile and inter story drifts obtained from nonlinear time history analysis using FBD approach



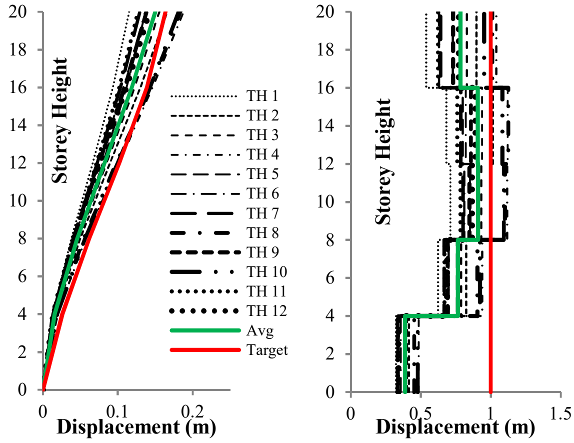
(a) Small Tank



(b) Medium Tank



(c) Large Tank



(d)Very Large Tank

Figure 8. Inelastic displacement profile and inter story drifts obtained from NL time history analysis using DDBD approach

7. CONCLUSION

The behavior and functional requirement of building frame and frame staging are significantly different from each other; hence, the prevalent DDBD approach for building frame cannot be used for the design of frame staging. Hence, in present study attempt was made to apply the established direct displacement based-design methodology to be used for the design of RC building frame to RC frame staging of elevated water tanks. The modified formulations (Equations (1)-(7)) are specifically developed based on the physical and dynamic characteristics of the elevated liquid tanks and can be considered as an innovative approach for this type of lifeline structures. Based on the inelastic displacements obtained from preliminary time history analysis, of force-based designed frame staging a characteristic displacement profile equation has been established. From nonlinear time history analysis, it has been observed that the inelastic displacement profile of the frame staging designed using the proposed DDBD approach shows good agreement with the proposed equation. Further, the inter-story drift results show that frame staging has maximum inter-story drift at middle level which also endorses the assumption of the middle level of frame staging as a critical story. In DDBD frame stagings uniform hinge formation observed in pushover analysis which highlights the uniform distribution of ductility over the height of the frame staging. The ratio of yield base shear to design base shear is relatively lower in case of DDBD approach than that of FBD approach. The maximum inter-story drift observed in all four tank frame stagings designed using DDBD approach is also well within the 1% drift limit. Nonlinear static and dynamic analyses demonstrate that the proposed DDBD approach gives better control over the desired performance of frame staging in terms of strength/capacity and inelastic displacement in anticipated seismic event.

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Direct Displacement Based Design of Reinforced Concrete Elevated Water Tanks Frame Staging

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چکیده

مخازن هوایی ذخیره آب با پایه های بتن مسلح به عنوان سازه های پاندول وارونه در نظر گرفته می شوند. این سازه ها از درجه اهمیت بالایی در زلزله برخوردار بوده و بایستی بتوانند بدون وقفه در حین زلزله و پس از آن انجام وظیفه نمایند. در بسیاری از آیین نامه های لرزه ای معتبر دنیا این مخازن بر اساس طراحی برمبنای نیرو محاسبه می گردند که رویکرد دقیقی نبوده و نمی تواند رفتار غیرخطی این سازه ها را به درستی در نظر گیرد. به همین دلیل طراحی این مخازن براساس روش های بر مبنای عملکرد مانند طراحی بر مبنای جابجایی ضروری به نظر می رسد. بسیاری از مهندسین محاسب به اشتباه رفتار این سازه ها را مانند ساختمان ها فرض نموده و طراحی عملکردی آنها را مشابه یک سازه ساختمانی در نظر می گیرند که مورد قبول نمی باشد. در پژوهش حاضر رویکرد طراحی عملکردی برای ساختمان ها مورد بازبینی قرار گرفته و با اعمال تغییراتی در روابط مربوطه آنها برای مخازن هوایی ذخیره آب اصلاح گردیده اند. برای این منظور رویکرد پیشنهادی بر روی یک مخزن هوایی با ارتفاع ۲۰ متر و چهار حالت مختلف پایه با رویکرد تحلیل غیرخطی بررسی گردیده است. در نهایت مقایسه ای میان طراحی برمبنای نیرو و تغییرمکان صورت گرفته و قابلیت های روش پیشنهادی مورد تجزیه و تحلیل قرار گرفته است.

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