Structural Engineering and Mechanics, *Vol. 62, No. 2 (2017) 209-224*
DOI: https://doi.org/10.12989/sem.2017.62.2.209

Estimation of response reduction factor of RC frame staging in elevated water tanks using nonlinear static procedure

Suraj O. Lakhade[a], Ratnesh Kumar* and Omprakash R. Jaiswal[b]

Department of Applied Mechanics, Visvesvaraya National Institute of Technology, Nagpur-440 010, India

(Received July 24, 2016, Revised December 31, 2016, Accepted January 10, 2017)

Abstract. Elevated water tanks are considered as important structures due to its post-earthquake requirements. Elevated water tank on reinforced concrete frame staging is widely used in India. Different response reduction factors depending on ductility of frame members are used in seismic design of frame staging. The study on appropriateness of response reduction factor for reinforced concrete tank staging is sparse in literature. In the present paper a systematic study on estimation of key components of response reduction factors is presented. By considering the various combinations of tank capacity, height of staging, seismic design level and design response reduction factors, forty-eight analytical models are developed and designed using relevant Indian codes. The minimum specified design cross section of column as per Indian code is found to be sufficient to accommodate the design steel. The strength factor and ductility factor are estimated using results of nonlinear static pushover analysis. It was observed that for seismic design category 'high' the strength factor has lesser contribution than ductility factor, whereas, opposite trend is observed for seismic design category 'low'. Further, the effects of staging height and tank capacity on strength and ductility factors for two different seismic design categories are studied. For both seismic design categories, the response reduction factors obtained from the nonlinear static analysis is higher than the code specified response reduction factors. The minimum dimension restriction of column is observed as key parameter in achieving the desired performance of the elevated water tank on frame staging.

Keywords: frame staging; strength factor; ductility factor; pushover analysis; elevated water tank; response reduction factor

1. Introduction

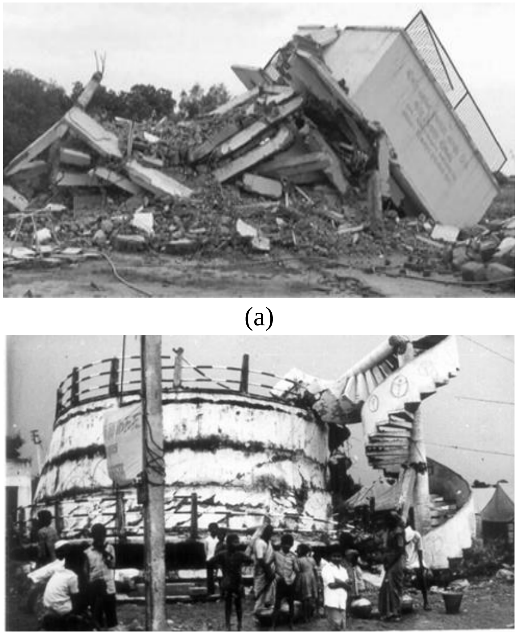
The post-earthquake importance of elevated water tanks is well known since in addition to provide potable water; it also provides water to extinguish post-earthquake fires. In most of the seismic design codes, water tanks are assigned with higher importance factors than ordinary buildings and are expected to exhibit a better performance during earthquakes and remain functional. In contrary, many water tanks during past earthquakes world over, have shown poor performance (Steinbrugge and Flores 1963, Mehrain 1990, Astaneh and Ashtiany 1990, Jain *et al*. 1994, Saffarini 2000, Rai 2002, Rai 2003). Figs. 1(a)-(b) shows collapsed elevated water tanks during Bhuj earthquake (Rai 2003) and Killari earthquake (Jain *et al*. 1994).

Rai (2002, 2003) studied the performance of elevated water tanks in Bhuj earthquake during which many water tanks suffered damage to their supporting structure and three water tanks were collapsed. It was pointed out that the possibility of failures of the frame staging under seismic overloads is more if the frame members and the beam-column joints are not designed and detailed for inelastic deformations. Moreover, Rai (2003) clearly pointed out that the damage to elevated water tank can be attributed to one or more of the following reasons; brace and column members do not meet the ductility and toughness requirements for earthquake resistance, brace-column joints were poorly detailed even for non-seismic moments, termination of longitudinal bars in the joint region, stirrups bent up at 90° instead of 135°, insufficient number of stirrups, poor quality of concrete and non-adherence to the design and detailing code viz. IS: 13920 (1993) and IS: 11682 (1985).

Generally, most of the seismic design codes (ASCE 7 2010, Eurocode 8 2006, IS 1893 part 1 2002) adopt force-based design methodology in which the anticipated seismic design force is reduced using single-valued response reduction factor (R). The response reduction factor depends on many factors such as over-strength, ductility and redundancy of the structure. The selection of seismic response reduction factor (R) is a key parameter in seismic design, which is related to the acceptable level of damage of structure under a defined hazard. Most of the force-based design codes consider life safety level as the minimum design criteria; however, the explicit identification of performance can only be achieved either by nonlinear analysis or experimentation. Since, the single-valued R factor for a particular class of structure covers the entire range of variation of that class of structure, it is expected that the R factor will provide a conservative design and the actual performance of the structure during anticipated

*Corresponding author, Assistant Professor
E-mail: ratnesh.eq@gmail.com
[a]Ph.D. Student
[b]Professor

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)



(a)

(b)

Fig. 1 Elevated water tank collapse during an earthquake (a) Bhuj earthquake (Rai 2003) (b) Killari earthquake (Jain *et al.* 1994)

seismic hazard will be either better or at least similar to the expected damage level. Several studies on investigation of the R factor for building have been conducted (Mitchell and Paultre 1994, Jain and Navin 1995, Kappos 1999, Elnashai and Mwafy 2002, Ozmen and Inel 2008, Kim *et al.* 2009, AlHamaydeh *et al.* 2011, Mondal *et al.* 2013, Chaulagain *et al.* 2014, Ozmen *et al.* 2014, Fanaie and Dizaj 2014, Chaulagain *et al.* 2015, Mohammadi *et al.* 2015, Massumi and Mohammadi 2016), however, very few studies are carried out to determine the seismic response factors for the elevated water tanks (Masoudi *et al*. 2012, Ghateh *et al.* 2015). ATC 19 (1995) is one of the primary documents which provide a detailed discussion on response modification factor. The primary emphasis of the document was to provide the basis of the values assigned to *R* for buildings in the seismic codes. However, the document provides means for decomposition of *R* factor in key components along with methods to evaluate the key components, which is useful for evaluation of R for other structures. Another document providing detailed guidelines for quantification of building seismic performance factors is FEMA P695 (2009). Primarily, the methods of FEMA P695 is applicable to building frame, however, the procedure is generalized and can be applied to other structures too. As discussed previously, the documents dealing with *R* factor are consistent with life safety performance objective which is the basic mandate of most of the seismic design codes on buildings. In the case of elevated water tanks, the basic question is how much damage shall be allowed so that the structure can remain operational even after the earthquake and correspondingly, what level of *R* factor can be assigned for this class of structures?

Past research on modelling of the elevated water tank can be broadly categorized into two groups viz. modelling of water and container, and the modelling of supporting structure. The research on modelling and analysis of water tanks gained impetus after 1960 Chilean earthquake in which significant damage to steel and reinforced concrete tanks were observed (Stembrugge and Clough 1960). This led to improvements in seismic design methodology of water tanks, such as consideration of two mass model, representing the impulsive and the convective mass of water (Housner 1963) and three mass model which includes additional effect of wall flexibility (Haroun and Housner 1981) in place of the single mass model (Chandrasekaran and Krishna 1954). Further, many improvements in modelling of water tanks were proposed by various researchers (Sonobe and Nishikawa 1969, Shepherd 1972, Chen and Barber 1976, Haroun and Ellaithy 1985, Veletsos and Tang 1990, Malhotra *et al.* 2000, Dutta *et al.* 2004, Livaoglu and Dogangun 2005, 2006, 2007a, 2007b, Dutta *et al.* 2009, Shakib *et.al.* 2010, Omidinasab and Shakib 2012, Livaoglu 2013). During this period the implementation of improved research findings was included in building codes time to time (Jaiswal *et al.* 2007). However, in the present study, the main focus is on the performance RC frame staging, rather than the behaviour of tank container, and thus the container and water have been modelled as lumped mass.

Masoudi *et al*. (2012) have estimated seismic response factors for elevated water tanks supported on both RC frame staging and RC pedestals. The effect of fluid structure interaction and P-Δ effect has been considered. It was observed that the frame staging in comparison to the building frames are less redundant and have limited capability to redistribute seismic induced moments. Moreover, while designing the frame staging the hinge formation in the columns should be prevented, and the hinges should be directed to the beam ends. Ghateh *et al.* (2015) employed a systematic approach to determine the seismic response factor for elevated water tanks supported on RC pedestals. The impulsive and convective water mass and the mass of container have been modelled as lumped mass. A wide range of tank sizes and pedestal heights has been considered. The nonlinear static analysis procedure is adopted to compute the seismic response factors.

The present study focuses on the nonlinear behavior of RC frame staging and the estimation of different components of response reduction factor. A wide range of tank models are selected based on various criteria viz. structural plan configuration, tank capacity, height of frame staging, and seismicity. The tank model dimensions and sizes are selected in accordance with the commonly constructed tank sizes and staging heights. In the study, the weight of tank container and water is modelled as lumped mass over the frame staging. In total, 48 tank models are analyzed and designed based on the requirements of IS 11682 (1985), IS 456 (2000) and IS 1893 part 2 (2014). Two levels of seismicity (seismic design category) are adopted for designing the tank models. The nonlinear static pushover analysis is carried out on each tank model. Finally, the seismic response factors are calculated from the pushover curves. However, it is important to note that in the present study, the nonlinear static procedure has been used which has some limitations in capturing the precise

Table 1 Drift limits corresponding to various damage states (ASCE 41-06 2007)

	Immediate occupancy	Life safety	Collapse prevention
Transient	1 %	2 %	4 %
Permanent	negligible	1 %	4 %

nonlinear dynamic behavior of the structure. Furthermore, the effect of liquid-structure interaction, soil-structure interaction and amplification of ground motion due to soil has also not been considered in the study, which may affect the results to a certain extent.

2. Expected seismic performance of elevated water tank and drift limit

Generally, for normal buildings, life safety structural performance is expected during the severe seismic event and the response reduction factors considered in various codes is to ensure this performance level. For concrete frames, ASCE 41-13 (2014) defines three structural performance levels viz. immediate occupancy, life safety and collapse prevention. Each of these performance levels are defined on the basis of levels of cracking, damage and hinge formation in the members. It also defines qualitatively the drift limits for each structural performance levels. Similarly, ASCE 41-06 (2007) quantitatively defines drift limits based on transient and permanent drifts as shown in Table 1. However, in case of water tank due to its post-earthquake importance, it is desired to have a better performance than buildings so as to retain the stability and uninterrupted functionality. Therefore, the allowable inelastic drift limit shall be limited to 1% and the response reduction factors shall be computed in such a way that the designed structure should satisfy the desired performance. Therefore, in the present study, the response reduction factor has been computed at 1% drift limit.

3. Parameters of response reduction factor (R)

The response reduction factor is generally a function of four key parameters of the structural system i.e., strength factor (R_s), ductility factor (R_μ), redundancy factor (R_R) and damping factor (R_ξ). However, the contribution of each of the key factor varies and depends on several parameters. In general, the response reduction factor (R) can be written as shown in Eq. (1). If the structures are not provided with dampers (supplemental energy devices) then the R_ξ value is assumed as 1.

$$R = R_s\, R_\mu\, R_R\, R_\xi \tag{1}$$

3.1 Strength factor (R_s)

From past earthquakes, it has been observed that structures possess overstrength i.e., the surplus strength than the design strength. In actual structure there are many reasons which contributes in overstrength (Whittaker and Rojahn 1999, Humar and Rahgozar 1996), such as, conservative models for determining the member capacity, structural members designed for higher capacities than the required, material strengths used in design to the strength used in determining the capacity, requirement from drift demand may govern the design, ratio of gravity load demand to seismic demand varies with seismic zones, local construction practices can influence the capacity of members and contribution of non-structural elements. Nevertheless, amongst the various aforementioned contributors of overstrength, only some of the parameters can be numerically estimated. Generally, the strength factor corresponding to collapse level is calculated as the ratio of maximum base shear ($V_{\max}$) determined from nonlinear analysis and the design base shear (V_d). However, it is expected that the elevated water tank being important structure, shall remain functional in case of anticipated design seismic event, therefore the maximum base shear ($V_{\max}$) at collapse level is not useful. Subsequently in the present study, the inelastic drift limit has been fixed to 1% of the total height of the frame staging (i.e., calculated from foundation to top of staging). The corresponding base shear at 1% drift (V_1) of the idealized pushover curve has been used to calculate strength factor (V_1/V_d). The pushover curves are bi-linearized using procedure of ASCE 41-13 (2014). In this procedure the first line segment of the idealized force-displacement curve starts at the origin and have slope equal to secant stiffness calculated at base shear equal to 60% of the effective yield strength. The second line segment has a positive post yield slope. This line intersects the first line segment in such a way that the areas above and below, between the idealized and the actual curves are approximately balanced (see Fig. 2). The intersection of first and second line segment indicates effective yield base shear (V_y) and effective yield displacement (Δ_y).

3.2 Ductility factor (R_μ)

The ductility factor is defined based on displacement ductility of the whole framing system. Despite the fact that ductility factor (R_μ) and displacement ductility ratio (μ) are closely related, they carry a different meaning. The displacement ductility ratio (μ) of a structure is the ratio of ultimate displacement ($\Delta_{\max}$) to effective yield displacement (Δ_y). The ductility factor (R_μ) quantifies the expected nonlinear response of the complete framing system, depending on the period of the structure. Several studies have been carried out to determine the ductility factor (R_μ) based on displacement ductility ratio (μ). The research work by Riddell and Newmark (1979), Newmark and Hall (1982), Fajfar and Krawinkler (1992), Miranda (1993) and Miranda and Bertero (1994) are notable in this area. The R-μ-T relationship proposed by Newmark and Hall (1982) provides a conservative lower bound value (Ghateh *et al.* 2015) and suitable for the water tank. Therefore, in the present study, this relationship has been used to calculate ductility factor. However, rather considering the ultimate displacement $\Delta_{\max}$, the displacement corresponding to 1% drift (Δ_1) has been considered keeping in view the desired performance of elevated water tank. The relationship of R_μ and μ are period (frequency) dependent. Generally, the elevated water tank on frame staging are long period structure and therefore, the ductility factor (R_μ) equal to displacement ductility ratio (μ) has been considered.

3.3 Redundancy factor (R_R)

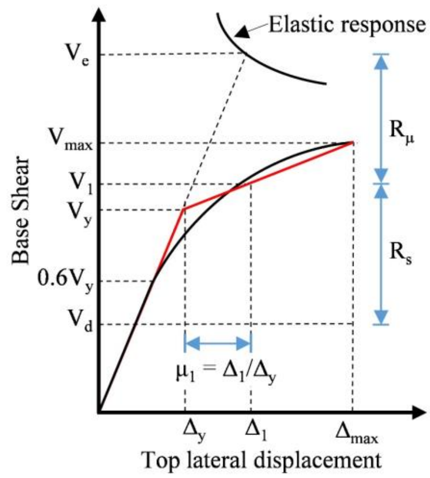
Redundancy can be defined as a number of alternate load paths available to transfer the load without failure of the entire system. In a framed structure (which is an assemblage of various members) various alternate load paths are available. Therefore, the failure of the complete system is delayed till the failure of the critical member/component, beyond which the entire structure is considered as failed. Bertero and Bertero (1999) classified two types of redundancy in a system, i.e., active type and standby type. A system is considered to have active redundancy when all the components are sharing loads. The systems with standby redundancy have active and inactive components. The inactive components become active only when some of the active components fail. In case of standby type, the redundancy factor is dependent on the over-strength and ductility of the structural system. In another study, Husain and Tsopelas (2004) and Tsopelas and Husain (2004) proposed explicit equations to study the effect of redundancy of RC buildings. They introduced two indices, the redundancy strength index and redundancy variation index to quantify the deterministic and probabilistic effects of redundancy, respectively. It was indicated by the authors that some of the factors used in computing redundancy factor was based on gravity load assumptions. Mohammadi *et al.* (2015) used the formulation proposed by Husain and Tsopelas (2004) on three dimensional building frames and computed the redundancy and reliability index.

It is generally observed that the shaft/pedestal staging of elevated water tank has lesser redundancy compared to the building frame (Rai 2002, Ghateh *et al.* 2015), since it has a single load path. However, in a realistic water tank frame staging, it is difficult to accurately define the redundancy factor since several members are available creating number of alternate load paths and therefore, the system redundancy can be categorized as standby type based on Bertero and Bertero (1999). Generally, the strength factor encompasses the effect of redundancy (Chaulagain *et al.* 2014) especially for standby type structures. In present study it is assumed that the redundancy factor is a part of strength factor and explicit computation of redundancy factor has not been considered.

3.4 Formulation adopted for response reduction factor

The formulation adopted for determining response reduction factor is given by Eq. (2), where R_s is the strength factor (V_1/V_d) which implicitly includes the contribution of the redundancy factor (R_R), and R_μ is the ductility factor corresponding to displacement ductility at 1% drift (Δ_1). Fig. 2 shows the components of seismic response factors.

$$R = R_s R_\mu \tag{2}$$



R_μ	Ductility factor
R_s	Strength factor
V_e	Elastic base shear
$V_{\max}$	Maximum base hear
V_1	Base shear corresponding to 1% drift on idealized curve
V_y	Effective yield base shear
V_d	Design base shear
Δ_y	Yield displacement
Δ_1	Displacement corresponding to 1% drift
$\Delta_{\max}$	Maximum displacement
μ_1	Displacement ductility ratio correspondi g to 1% drift

Fig. 2 Seismic response factors

It is important to note that the factors R_s and R_μ are sensitive to bi-linearization method of the pushover curves. Many methods of bi-linearization are presented in literature (Park 1988, Priestley and Park 1987, Paulay and Priestley 1992, ATC 19 1995, ATC 40 1996, Kadas 2006, ASCE 41-13 2014), however, four common methods are, bi-linearization based on first yield, based on equivalent elasto-plastic yield, based on equivalent elasto-plastic energy absorption and based on reduced stiffness equivalent elasto-plastic yield (Park 1988). In present study the bi-linearization procedure of ASCE 41-13 (2014) based on effective lateral stiffness and effective yield strength has been used.

4. Description of the tank models considered for the study

The models for the study are selected on the basis of various criteria such as staging height, tank capacity, structural plan configuration of frame staging, site seismicity (seismic design category) and response reduction factor. Three frame staging heights of 16, 20 and 24 m and four tank capacities i.e., 0.09 Ml (Megaliters), 0.6 Ml, 1.7 Ml, 2.6 Ml, representing small, medium, large and very large tanks, respectively, are considered for the study. Based on the considered tank capacities four staging plan configuration are considered. For the small tank capacity 4 column configuration, for medium tank capacity 12 column

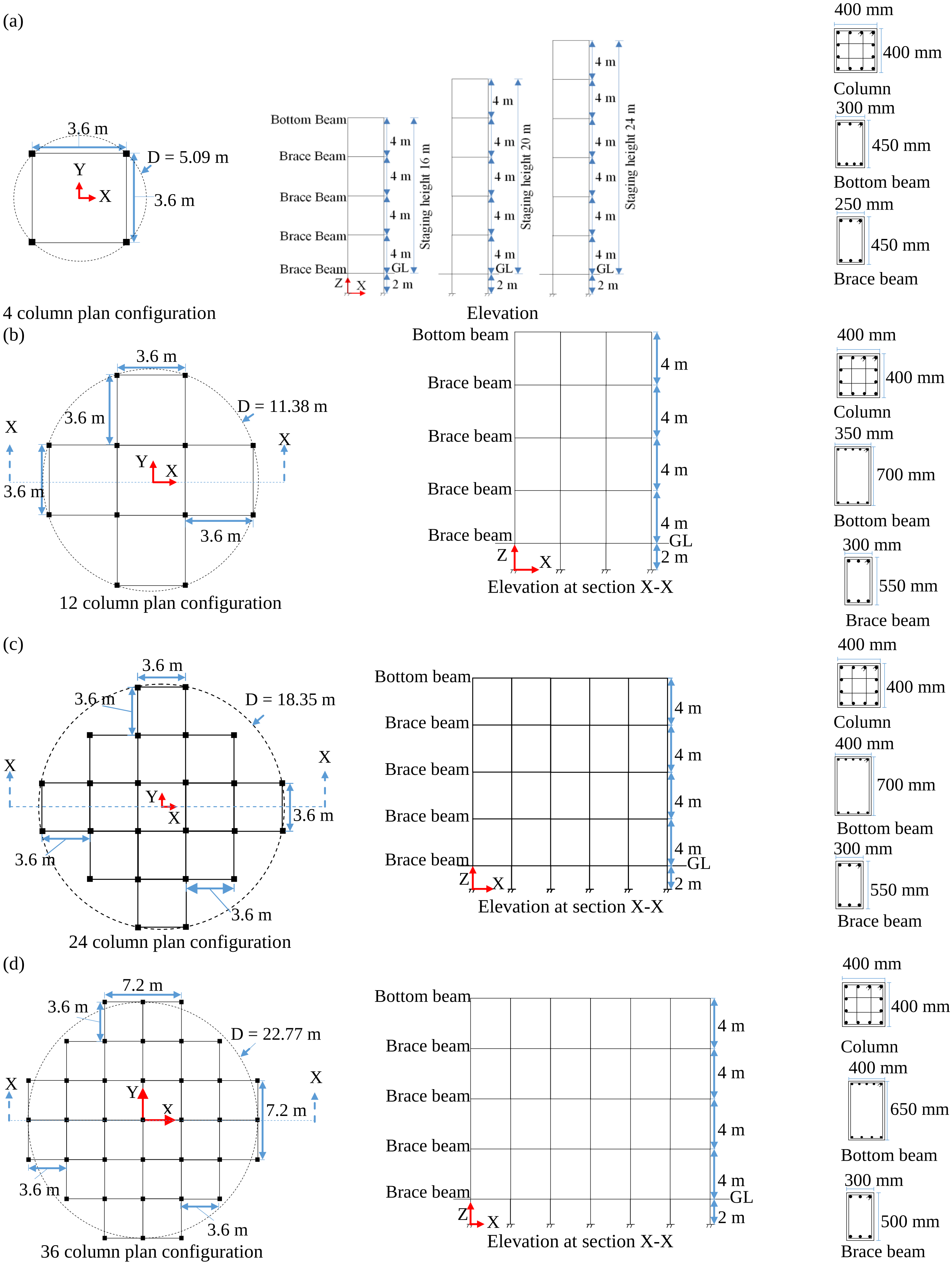


Fig. 3 Staging plan configuration and typical member sizes for different tank capacity (a) small, (b) medium, (c) large, (d) very large

Table 2 Specification of tank models

Model ID	Staging height (m)	Design load level		Tank Capacity (ml)	Normalized base shear* (%)	
		Seismic design category	Tank category		R=2.5	R=4
16-H-0.09	16	High	Small	0.09	11.47	7.19
16-H-0.6			Medium	0.6	10.82	6.76
16-H-1.7			Large	1.7	10.15	6.34
16-H-2.6			Very large	2.6	10.04	6.27
16-L-0.09		Low	Small	0.09	1.58	0.93
16-L-0.6			Medium	0.6	1.25	0.78
16-L-1.7			Large	1.7	1.17	0.73
16-L-2.6			Very large	2.6	1.21	0.76
20-H-0.09	20	High	Small	0.09	9.81	6.15
20-H-0.6			Medium	0.6	9.43	5.90
20-H-1.7			Large	1.7	8.90	5.56
20-H-2.6			Very large	2.6	8.84	5.53
20-L-0.09		Low	Small	0.09	1.28	0.82
20-L-0.6			Medium	0.6	1.03	0.64
20-L-1.7			Large	1.7	0.97	0.61
20-L-2.6			Very large	2.6	1.01	0.63
24-H-0.09	24	High	Small	0.09	8.65	5.42
24-H-0.6			Medium	0.6	8.39	5.24
24-H-1.7			Large	1.7	7.98	4.99
24-H-2.6			Very large	2.6	7.96	4.98
24-L-0.09		Low	Small	0.09	1.08	0.72
24-L-0.6			Medium	0.6	0.89	0.56
24-L-1.7			Large	1.7	0.84	0.52
24-L-2.6			Very large	2.6	0.87	0.55

*design base shear normalized to the seismic weight

configuration, for large tank capacity 24 column configuration and for very large tank 37 column configuration as shown in Fig. 3 are considered. The seismicity of site plays important role in computation of seismic design base shear. The ratio of gravity load and seismic design base shear varies with the seismicity of site, which in turn affects the response reduction factor significantly. In the present study two levels of seismic design categories are considered and indicated as ‘high’ and ‘low’ in Table 2. The consideration of seismic design category ‘high’ and ‘low’ is based on seismic zones *V* and II of Indian Standard IS 1893 part 1 (2002). The Indian Standard defines the PGA of 0.36g for the highest seismic zone (Zone V) and 0.1g for the lowest seismic zone of India (Zone II) corresponding to the maximum considered earthquake (MCE) and uses a multiplication factor of 0.5 to convert it into design basis earthquake (DBE). All the considered tanks are assumed to be resting on hard soil. IS 1893 part 2 (2014), provides two values of the response reduction factor (R) for elevated water tanks supported on frame staging. If the tank is supported on ordinary moment resisting frame the R is 2.5 and if the tank is supported on special moment resisting frame conforming to the ductility requirements of IS 13920 (1993) the R is 4. In the present study, the tanks are designed for both the aforementioned R factors, and examined using pushover analysis. Elevated water tanks being an important structure, the Importance factor I of 1.5 is considered. The seismic design base shear is computed using the equivalent static method of IS 1893 part 2 (2014). Concrete grade of M30 having the characteristic cube strength of 30 MPa and modulus of elasticity of 27386 MPa and steel grade of Fe415 having yield strength of 415 MPa and modulus of elasticity of 2×10^5 MPa are used in design. The elastic drift limit of all the forty-eight elevated tank models have been checked and found to be well within the prescribed limit of IS 1893 Part 1 (2002) (i.e., 0.4 percent of the height of staging).

Based on the combinations of tank staging height, capacity, seismic design category (SDC) and response reduction factors, forty-eight elevated tank models are developed as shown in Table 2. Each tank model has been designated with a unique model number based on staging height, SDC and tank capacity. For example, model ID 16-H-0.09 stands for an elevated water tank with 16 m staging height, designed for SDC ‘high’ and tank capacity of 0.09 Ml (90000 liters). Out of the three parts of the elevated water tank i.e., container, staging and foundation, the primary focus of the study is on behavior of staging. Therefore, rather using a complicated model for container and liquid, the mass of water and the container are distributed over the bottom beam and the foundation is modelled as fixed by constraining all the six degrees of freedom at bottom of the columns. While designing the tank models, first the minimum dimensions of columns and braces based on IS 1893 part 2 (2014) (minimum column cross section is 400 mm×400 mm and minimum brace cross section is 200 mm×200 mm) are considered in the three-dimensional model. The lateral stiffness of the structure is calculated and the base shear is obtained taking the complete mass of liquid as impulsive (IS 1893 part 2 2014).

The design base shear is applied at the center of gravity of the container. Then the analysis of the tank model is carried out followed by design. Further, the adequacy of cross sections of braces and columns are checked along with limiting the reinforcement in column cross section within 4% and limiting reinforcement in brace cross section within 2.5% (with limiting the maximum reinforcement of 1.5% on either face of the brace). If the cross sections are found unsafe or exceeding the specified reinforcement limits, the sections are revised. The sections are designed as per the provisions of IS 456 (2000). While designing the tank models for seismic design category ‘low’, the minimum code specified dimensions of columns and braces were safe to carry loads except the bottom beams. In the case of an elevated water tank, the maximum load is concentrated at the top of the frame staging and hence the bottom beam is generally having bigger dimensions than the braces. For seismic design category ‘high’ the minimum column dimension is found sufficient to accommodate the design reinforcement but the brace sections are increased

Table 3 Dimensions and typical percentage reinforcement of the members of tank models

Model ID	Bottom beam	Brace beam	Column	R=2.5			R=4		
				Reinforcement (%)			Reinforcement (%)		
	Size (cm)	Size (cm)	Size (cm)	Bottom Beam (Top/ Bot.)	Brace Beam (Top /Bot.)	Column *	Bottom Beam (Top/ Bot.)	Brace Beam (Top/ Bot.)	Column *
16-H-0.09	30×45	25×45	40×40	0.98/0.67	1.2/1.21	3.65	0.74/0.52	0.69/0.7	2.98
16-H-0.6	35×70	3 × 55	40×40	0.61/0.32	1.42/0.75	3.48	0.5/0.32	0.98/0.49	2.5
16-H-1.7	40×70	30×55	40×40	0.58/0.32	1.43/0.80	3.37	0.5/0.32	0.99/0.49	2.64
16-H-2.6	40×65	30×50	40×40	0.67/0.33	1.53/0.83	3.63	0.58/0.32	1.08/0.54	2.67
16-L-0.09	30×40	20×20	40×40	0.86/0.43	0.67/0.60	3.17	0.75/0.38	0.4/0.32	2.93
16-L-0.6	30×70	20×20	40×40	0.44/0.32	1.15/0.57	1.62	0.41/0.32	0.84/0.42	1.35
16-L-1.7	30×75	20×20	40×40	0.52/0.26	1.15/0.57	1.34	0.5/0.25	0.83/0.41	0.96
16-L-2.6	30×75	20×20	40×40	0.5/0.25	1.13/0.68	1.32	0.48/0.24	0.8/0.4	0.95
20-H-0.09	30×45	25×45	40×40	0.85/0.59	0.95/0.91	3.47	0.69/0.52	0.6/0.6	2.98
20-H-0.6	35×70	30×55	40×40	0.57/0.32	1.36/0.68	3.29	0.47/0.32	0.96/0.48	2.45
20-H-1.7	40×70	30×55	40×40	0.55/0.32	1.37/0.69	3.43	0.48/0.32	0.95/0.48	2.58
20-H-2.6	40×65	30×50	40×40	0.63/0.32	1.45/0.73	3.43	0.55/0.32	1.03/0.52	2.62
20-L-0.09	30×40	20×20	40×40	0.82/0.41	0.67/0.57	3.08	0.75/0.37	0.43/0.34	2.93
20-L-0.6	30×70	20×20	40×40	0.39/0.32	1.16/0.58	1.69	0.37/0.32	0.89/0.44	1.48
20-L-1.7	30×75	20×20	40×40	0.52/0.26	1.14/0.57	1.39	0.5/0.25	0.86/0.43	1.09
20-L-2.6	30×75	20×20	40×40	0.49/0.32	1.12/0.57	1.4	0.47/0.24	0.83/0.41	1.1
24-H-0.09	30×45	25×45	40×40	0.85/0.61	0.94/0.9	3.46	0.66/0.46	0.56/0.53	2.91
24-H-0.6	35×70	30×55	40×40	0.54/0.32	1.33/0.66	3.19	0.44/0.32	0.95/0.47	2.44
24-H-1.7	40×70	30×55	40×40	0.52/0.32	1.32/0.66	3.25	0.45/0.32	0.94/0.47	2.53
24-H-2.6	40×65	30×50	40×40	0.61/0.32	1.4/0.7	3.27	0.54/0.32	1.01/0.51	2.59
24-L-0.09	30×40	20×20	40×40	0.8/0.4	0.65/0.55	3	0.73/0.37	0.44/0.34	2.9
24-L-0.6	30×70	20×20	40×40	0.35/0.32	1.18/0.59	1.77	0.33/0.32	0.94/0.47	1.6
24-L-1.7	30×75	20×20	40×40	0.51/0. 32	1.15/0.57	1.47	0.49/0.24	0.89/0.45	1.21
24-L-2.6	30×75	20×20	40×40	0.48/0.32	1.12/0.57	1.48	0.47/0.23	0.86/0.43	1.24

*reinforcement shown is for the columns just below the bottom beam, for lower columns the reinforcement reduces and most of the bottom columns are having only 0.8% reinforcement (minimum specified in IS 456 2000).

and optimized to maintain the desired reinforcement percentages. By following the aforementioned criteria, the strong column weak beam condition is achieved in the models designed for *R*=4, however, for models designed for *R*=2.5 the same has not been achieved. The typical reinforcement detailing for the tank models designed for R as 2.5 and 4 for various staging heights and capacities under seismic design category ‘high’ and ‘low’ are shown in Table 3.

5. Modelling of RC frame staging

The general purpose software SAP 2000 (2004) nonlinear is used for the modelling of the RC frame staging of elevated water tanks. The columns and braces are modelled using frame elements. The frame element is having 6-degree of freedom at each connecting joint with the capability of including the effect of biaxial bending, torsion, axial deformation and biaxial shear deformation. To consider the effect of tank bottom slab rigidity, the rigid diaphragm constraint is used. The nonlinearity in frame elements are provided using lumped plasticity models as per FEMA 356 (2000) /ASCE 41-13 (2014). In case of braces, uncoupled moment hinges (M3) and for column members, coupled axial force and biaxial bending moment hinges (P-M2-M3), have been assigned at both the ends of the members.

6. Nonlinear static pushover analysis

Pushover is a static nonlinear analysis method where a structure is subjected to gravity loading and then to the lateral loading whose magnitude is increased incrementally in line with a predefined load pattern and the corresponding top displacement is recorded. In this study, the lateral load is applied in accordance with the fundamental mode shape, since the modal mass participation factor of the first mode is above 90%. The pushover curve is plotted as top lateral displacement and corresponding base shear. The bi-linearization of pushover curves is carried out using the procedure suggested in ASCE 41-13 (2014) and accordingly, the effective yield displacement and effective base shear has been calculated.

Forty-eight pushover curves were developed for the models listed in Table 2. The pushover curves for seismic design category ‘high’ and ‘low’ are shown in Figs. 4(a)-(d) and Figs. 5(a)-(d), respectively. From the pushover analysis it is observed that in the models designed for *R*=2.5, the hinge formation starts in the lower brace beams followed by hinge formation in column and upper brace beams, however, for the models designed for *R*=4 the hinge formation starts in the column only after all the hinges are formed in the brace beams. As discussed previously, the column cross section is governed by minimum size requirement and therefore, initial slope of the pushover curve for both types of models (*R*=2.5 and *R*=4) are almost same. As anticipated, the maximum base shear of models designed for *R*=2.5 is more than the models designed for *R*=4. Similarly, the maximum top lateral displacement corresponding to maximum base shear is more in the models designed for *R*=4 than the models designed for *R*=2.5. It can be seen from Figs. 4(a)-(d) and Figs. 5(a)-(d) that invariably the maximum base shear and base shear corresponding to 1% drift reduces with increase in staging height. This is in line with reduction of design base shear for taller staging. For seismic design category ‘high’, in comparison to 16 m staging height the maximum base shear

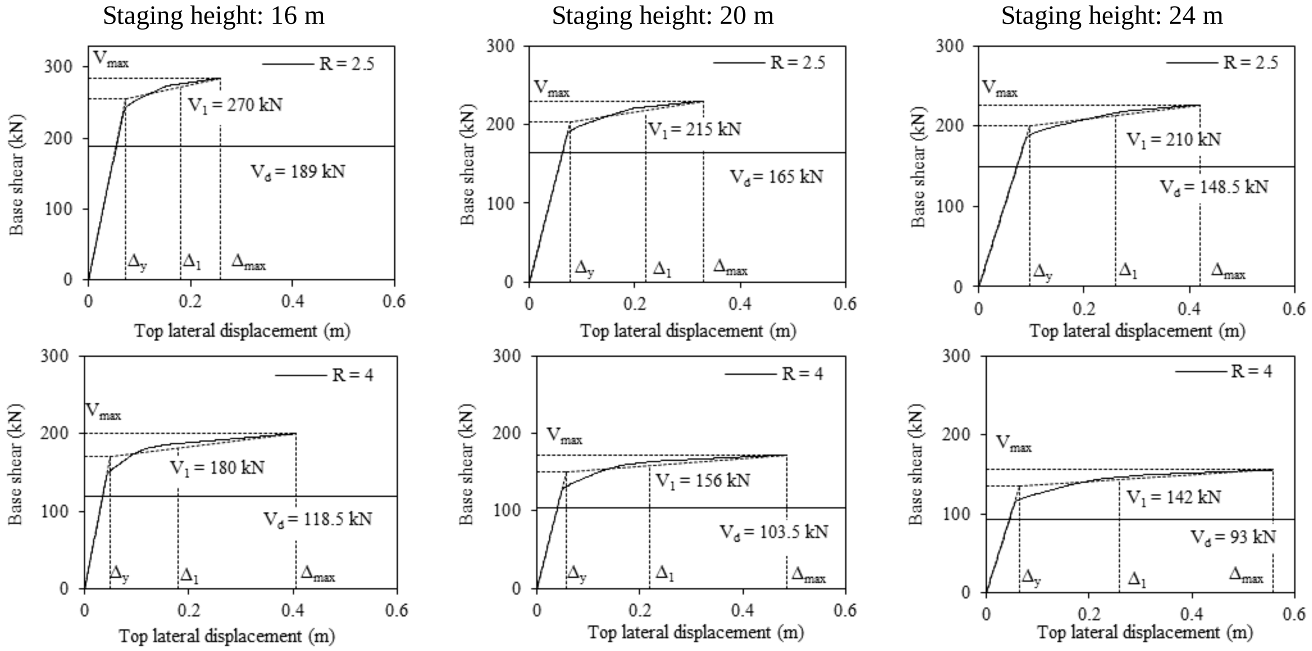


Fig. 4(a) Pushover curves for tank capacity 0.09 ml designed for SDC 'high'

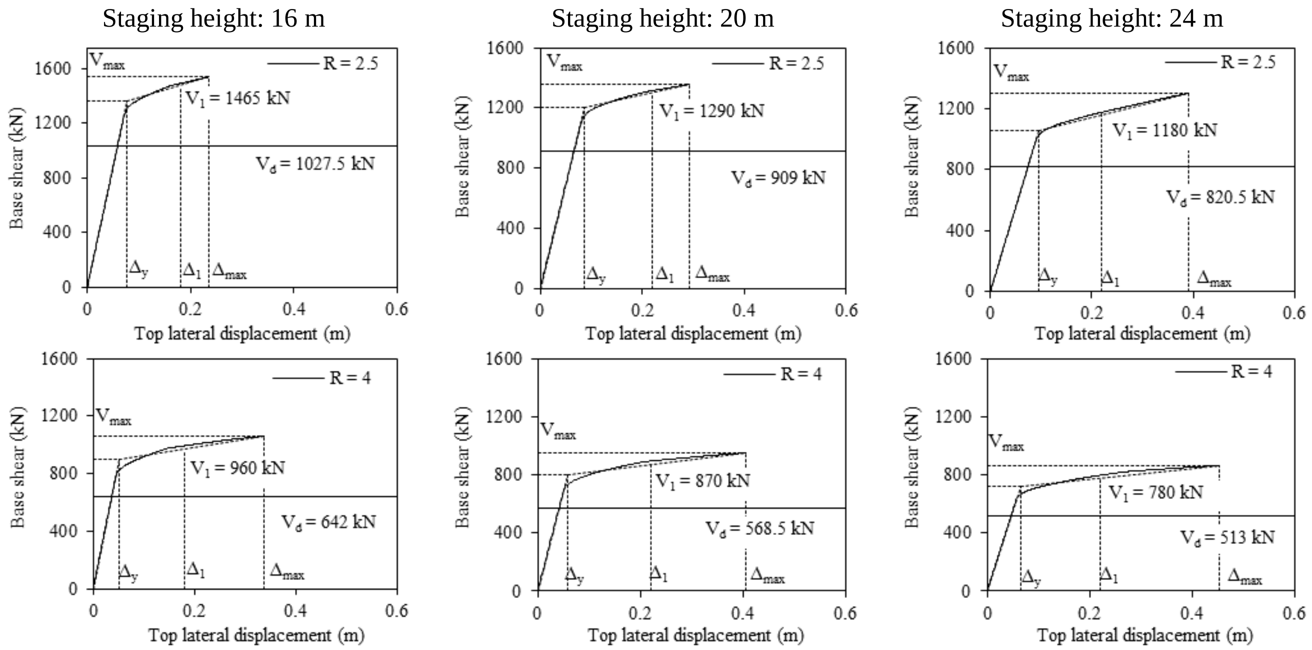


Fig. 4(b) Pushover curves for tank capacity 0.6 ml designed for SDC 'high'

approximately reduces by 12% and 23% for staging height 20 m and 24 m, respectively. This effect for the 1.7 Ml tank for SDC 'high' is shown in Fig. 6. Similarly, for seismic design category 'low', in comparison to 16 m staging height the maximum base shear approximately reduces by 18% and 38% for staging height 20 m and 24 m, respectively. These percentage variations of base shear are not affected by tank capacity. The effect of staging height and corresponding maximum base shear can be correlated to design base shear. With increase in staging height the fundamental period of the models increases, thereby reducing the design base shear. It is also important to note that with increase in staging height stiffness is reducing and thus the yield displacement is increasing. It is also observed that with increase in tank capacity the initial slope of the pushover curve is increasing, however, the yield and maximum displacement more or less remains constant. This trend for a 20 m staging model for SDC 'high' is shown in Fig. 7.

7. Seismic response factors

As discussed in section 3.4, the seismic response factors i.e., R_s and R_μ are obtained from nonlinear static pushover

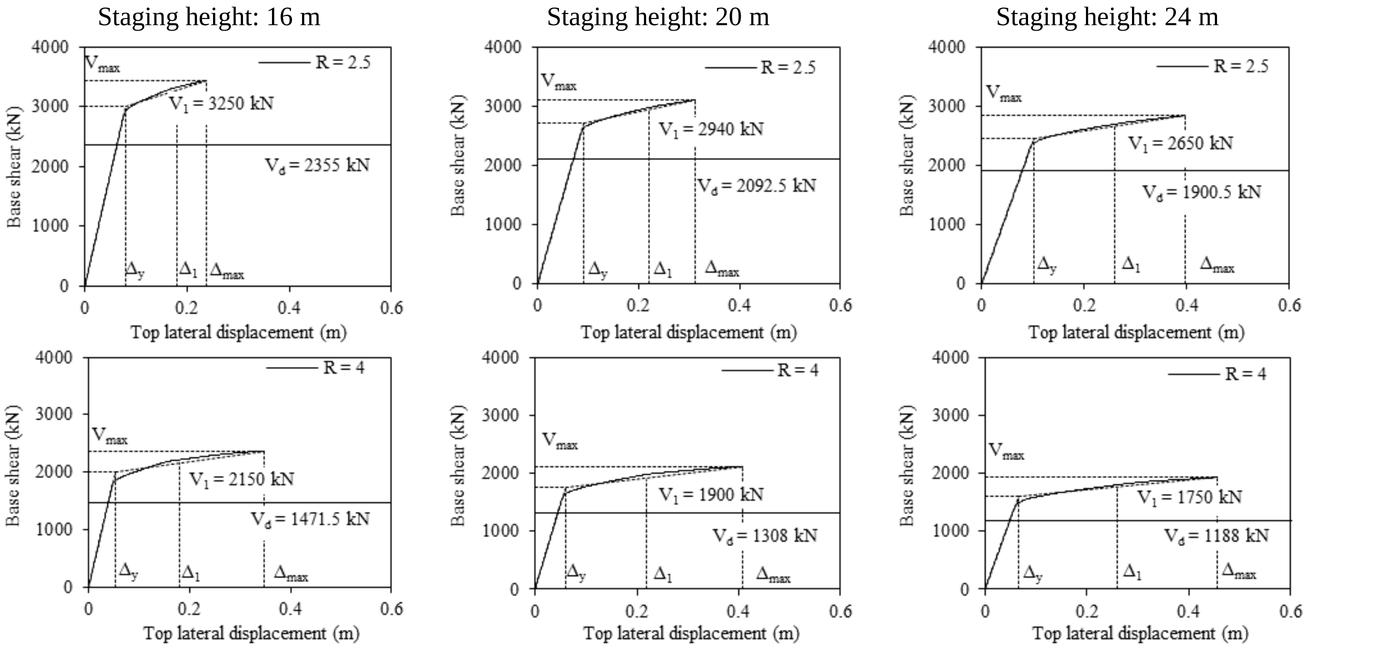


Fig. 4(c) Pushover curves for tank capacity 1.7 ml designed for SDC ‘high’

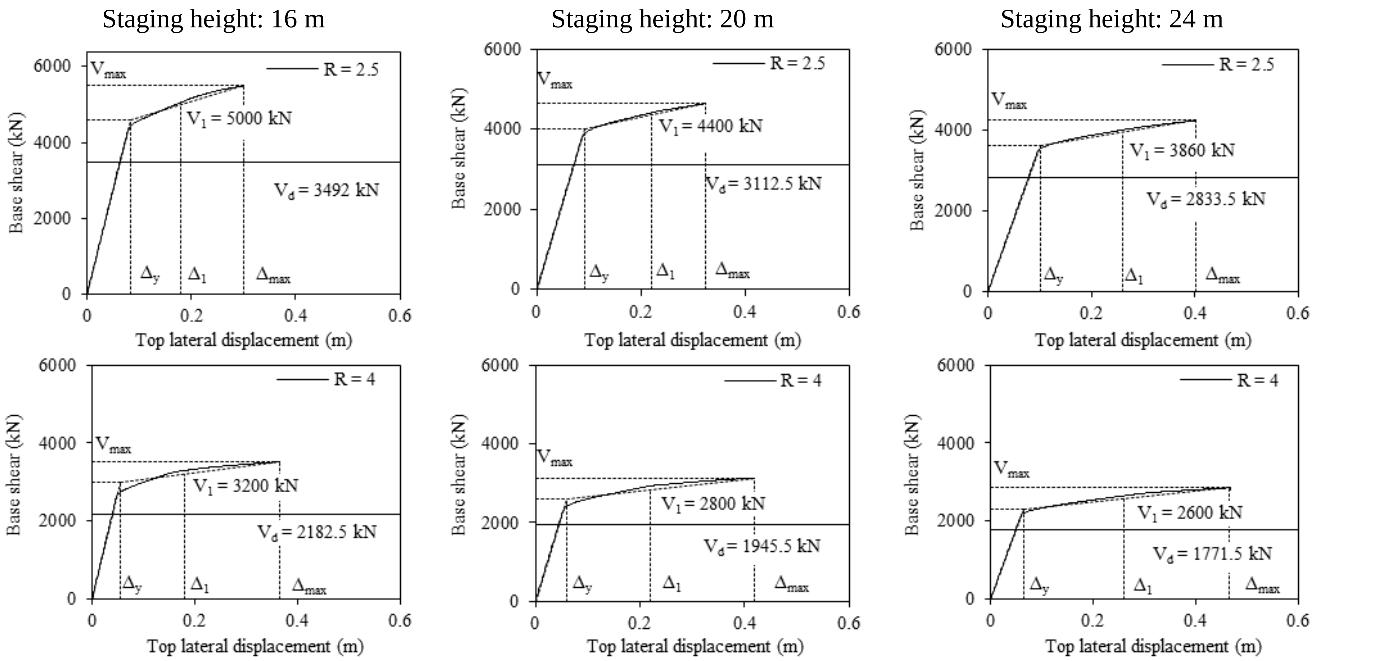


Fig. 4(d) Pushover curves for tank capacity 2.6 ml designed for SDC ‘high’

curves for the criteria considered in section 6. The strength and ductility factors of the various models for seismic design category ‘high’ and ‘low’ are shown in Table 4. For SDC ‘high’ there is small increase (about 6%) in strength factor for the models designed for R=4 than the models designed for R=2.5, however, the increase in ductility factor is significant (about 49%). In case of SDC ‘low’ the effect is opposite i.e., the increase in strength factor is significantly high (about 37%) and the increase in ductility factor is small (about 4%) for the models designed for R=4 than the models designed for R=2.5. This behavior for SDC ‘low’ can be attributed to the fact that the design sizes for frame members are governed by the minimum criteria rather than required by analysis, leading to high strength factor. Moreover, due to larger member sizes the effective yield base shear increases, congruently increasing the effective yield displacement and thus leading to smaller increase in ductility factor at the considered 1% drift limit.

7.1 Effect of staging height

The effect of staging height on ductility factor is shown in Fig. 8(a). It can be observed from the figure that in the case of SDC ‘high’, the ductility factor increases with the

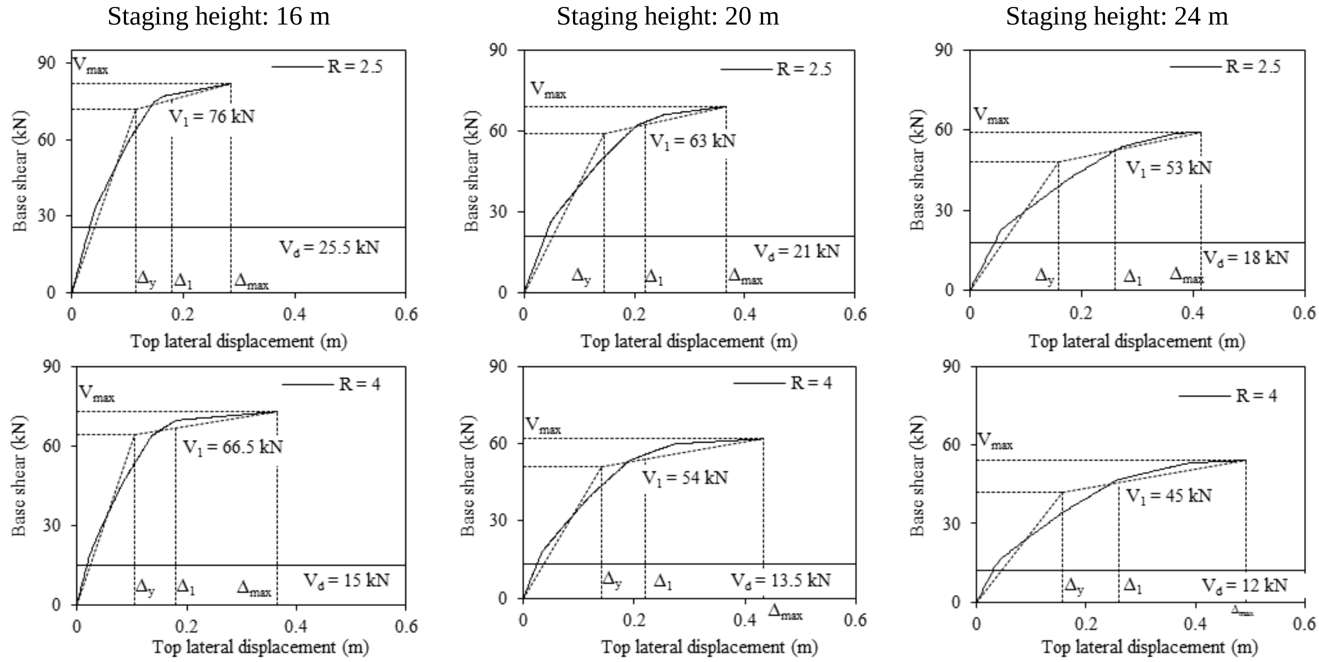


Fig. 5(a) Pushover curves for tank capacity 0.09 ml designed for SDC 'low'

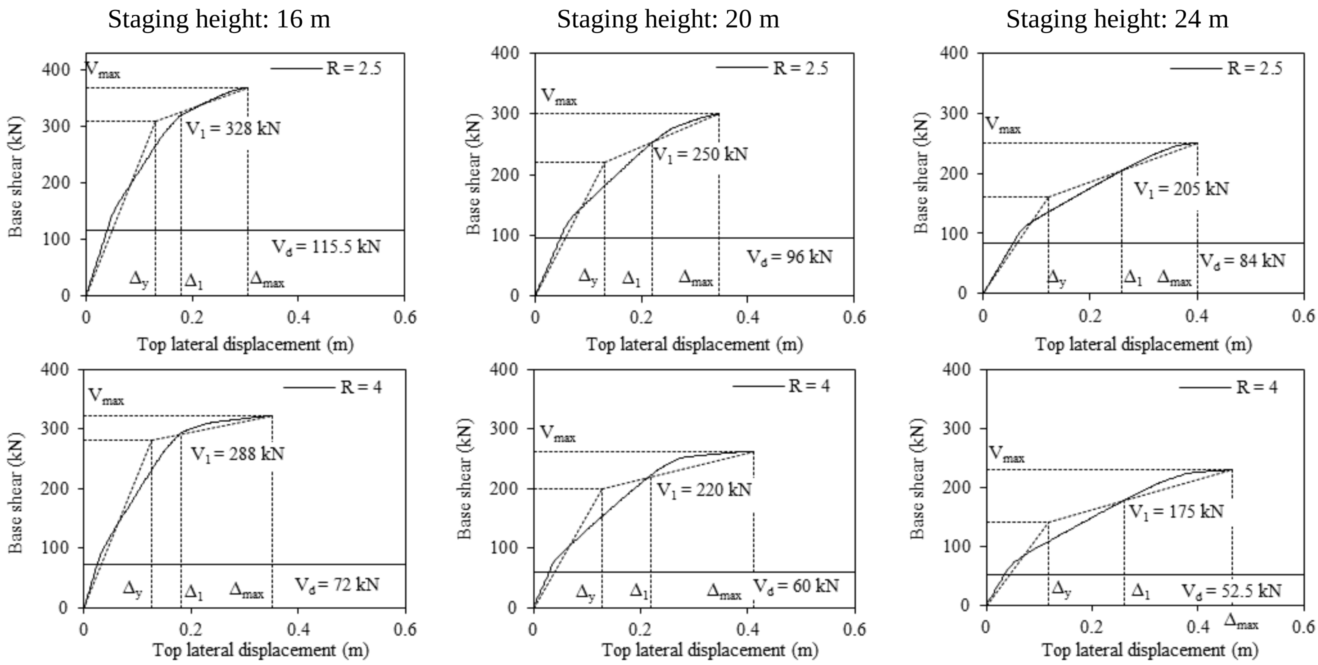


Fig. 5(b) Pushover curves for tank capacity 0.6 ml designed for SDC 'low'

increase in staging height whereas; in the case of SDC 'low' the effect of change in staging height on ductility factor is only marginal. The effect of staging height on strength factor is shown in Fig. 8(b). It can be observed from the figure that in the case of SDC 'low', the value of strength factor marginally decreases with the increase in staging height. This decrease is more prominent for low capacity tanks designed for R=4. Moreover, in the case of SDC 'high', the effect of staging height on strength factor is negligible.

7.2 Effect of tank capacity

The effect of tank capacity on the seismic response factors is shown in Figs. 9(a)-(b). In the case of SDC 'high', the effect of tank capacity on ductility factor is negligible. While, in case of SDC 'low', mostly the ductility factor increases with the increase in tank capacity for 0.09 Ml, 0.6 Ml and 1.7 Ml, however, for tank capacity of 2.6 Ml the ductility factor decreases. The effect of tank capacity on strength factor is shown in Fig. 9(b). It can be observed

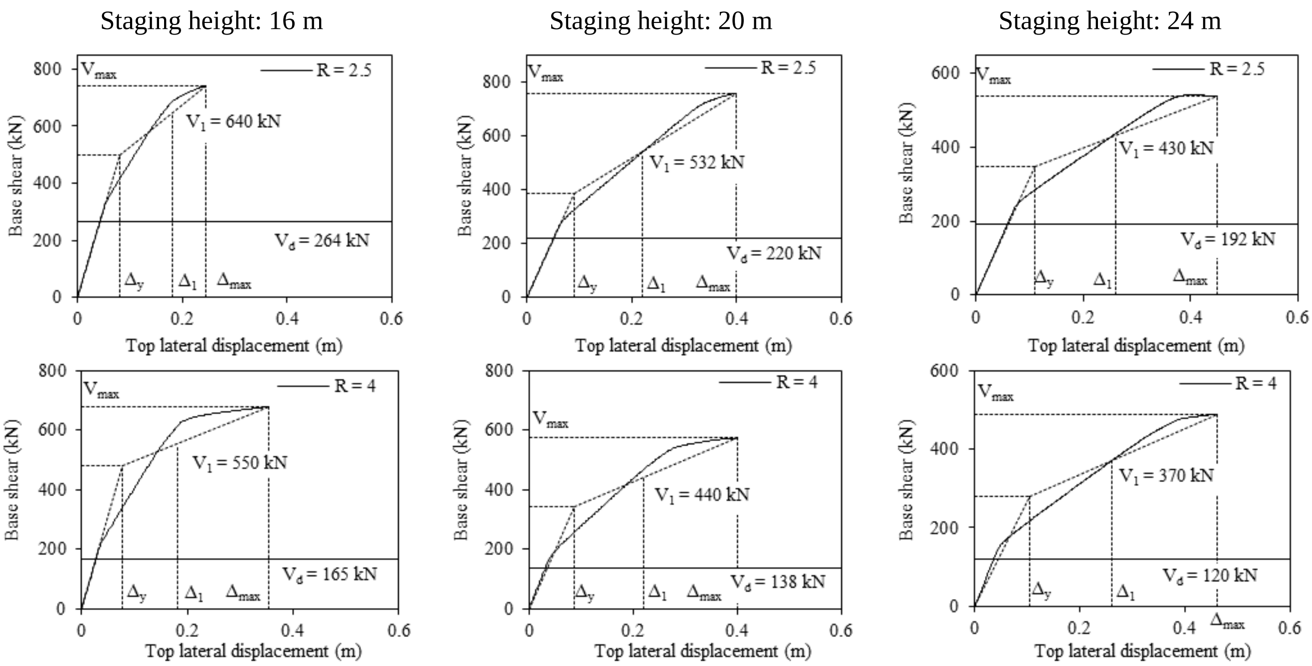


Fig. 5(c) Pushover curves for tank capacity 1.7 ml designed for SDC ‘low’

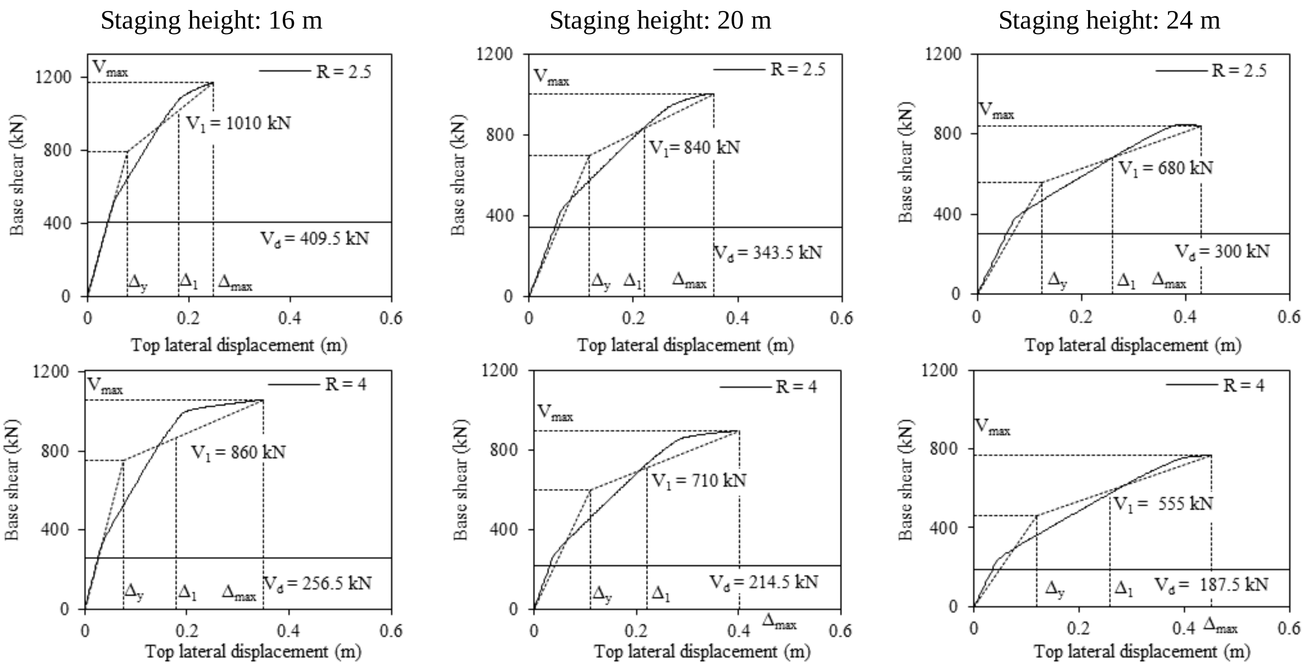
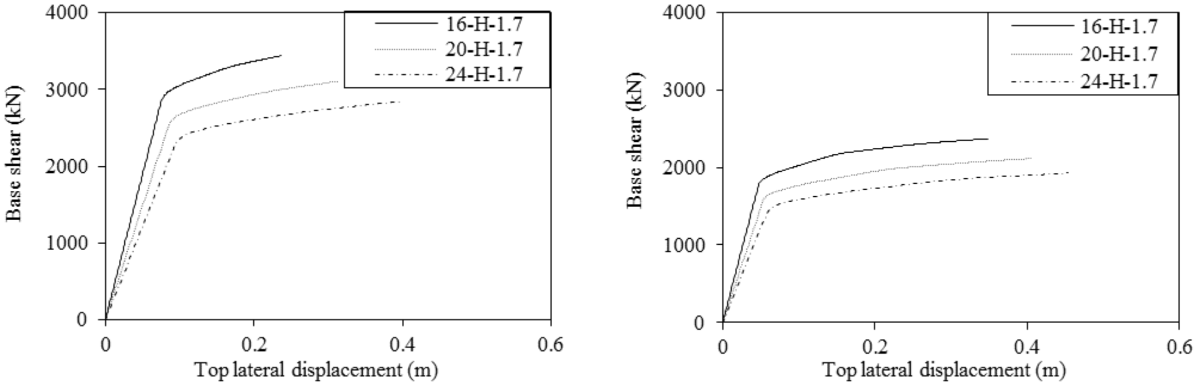


Fig. 5(d) Pushover curves for tank capacity 2.6 ml designed for SDC ‘low’

from the figure that in the case of SDC ‘low’, the strength factor decreases with the increase in tank capacity. Whereas, in the case of SDC ‘high’ effect of tank capacity on the strength factor is not significant.

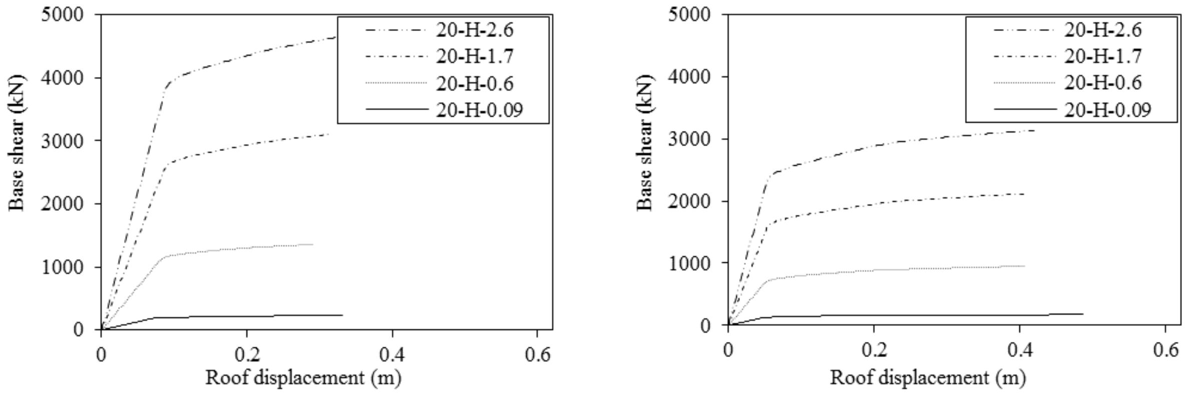
8. Response reduction factor

The seismic response factors are determined for 48 tank models and grouped with respect to tank capacities. The average value of strength and ductility factors for the three staging heights i.e., 16 m, 20 m and 24 m are shown in Table 5 for SDC ‘high’ and ‘low’. In general, it can be observed from the table that the strength factor is smaller for SDC ‘high’ than SDC ‘low’. For SDC ‘high’ the strength factor remains more or less same for a particular R value and not influenced by the tank capacity. However, in case of SDC ‘low’ the strength factor is more for low capacity tanks and marginally reduces with increase in tank capacity. In contrary to the strength factor, the ductility factors are higher for SDC ‘high’ than SDC ‘low’. Moreover, no distinct pattern of change in ductility factor



(a) Designed for *R*=2.5 (b) Designed for *R*=4

Fig. 6 Effect of staging height on pushover curve keeping tank capacity constant as 1.7 Ml for SDC 'high'



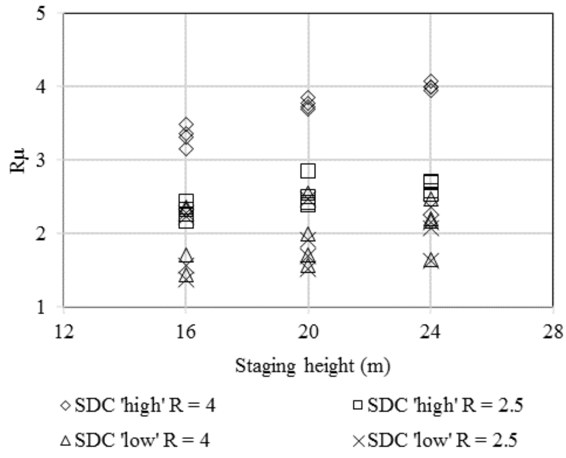
(a) Designed for *R*=2.5 (b) Designed for *R*=4

Fig. 7 Effect of tank size on pushover curve keeping staging height constant as 16 m for SDC 'high'

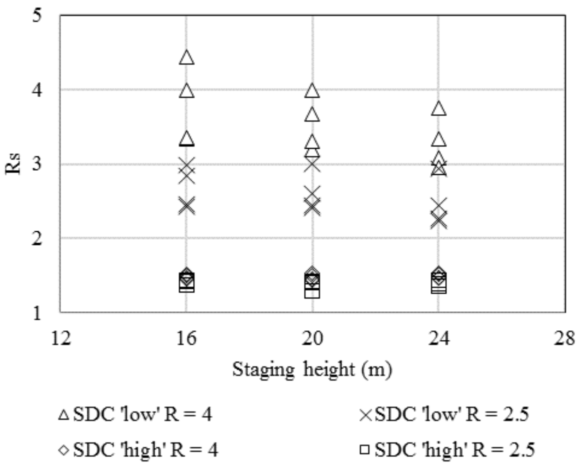
Table 4 Seismic response factors for seismicity design category 'high' and 'low'

SDC 'high'					SDC 'low'				
Model ID	R_s		$R\mu$		Model ID	R_s		$R\mu$	
	R=2.5	*R*=4	*R*=2.5	*R*=4		*R*=2.5	*R*=4	*R*=2.5	*R*=4
16-H-0.09	1.4	1.5	2.4	3.2	16-L-0.09	3.0	4.4	1.6	1.7
20-H-0.09	1.3	1.5	2.8	3.9	20-L-0.09	3.0	4.0	1.5	1.6
24-H-0.09	1.4	1.5	2.7	4.0	24-L-0.09	2.9	3.8	1.6	1.6
16-H-0.6	1.4	1.5	2.3	3.5	16-L-0.6	2.8	4.0	1.4	1.4
20-H-0.6	1.4	1.5	2.5	3.8	20-L-0.6	2.6	3.7	1.7	1.7
24-H-0.6	1.4	1.5	2.7	4.0	24-L-0.6	2.4	3.3	2.1	2.2
16-H-1.7	1.4	1.5	2.3	3.4	16-L-1.7	2.4	3.3	2.2	2.3
20-H-1.7	1.4	1.5	2.4	3.7	20-L-1.7	2.4	3.2	2.5	2.6
24-H-1.7	1.4	1.5	2.6	3.9	24-L-1.7	2.2	3.1	2.4	2.5
16-H-2.6	1.4	1.5	2.2	3.3	16-L-2.6	2.5	3.4	2.3	2.4
20-H-2.6	1.4	1.4	2.4	3.7	20-L-2.6	2.4	3.3	1.9	2.0
24-H-2.6	1.4	1.5	2.5	4.1	24-L-2.6	2.3	3.0	2.1	2.2

with tank capacity is observed. For both seismic design categories, the response reduction factors obtained from the nonlinear static analysis is higher than the code specified designed response reduction factors. The obtained response reduction factor is approximately 1.4 times higher for SDC 'high' and 2 times higher for SDC 'low'. It is important to note that the specified minimum member dimension (IS 1893 part 2 2014) is the key consideration in achieving the desired performance of water tank on frame staging. Moreover, in the present study the *R* factors have been computed using nonlinear static procedure which has certain limitations in capturing the precise nonlinear response. Also, the effect of fluid-structure interaction, soil-structure interaction and ground motion amplification due

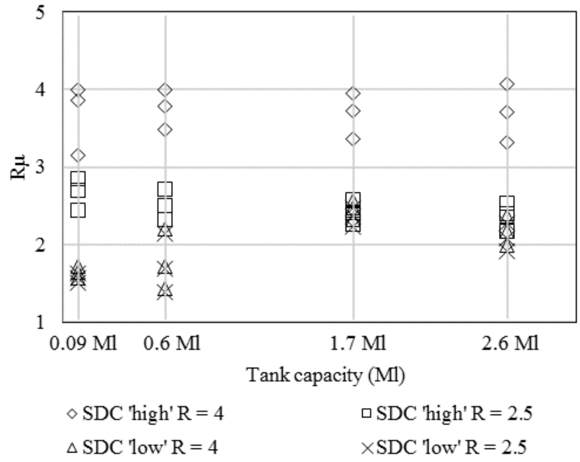


(a) Ductility factor

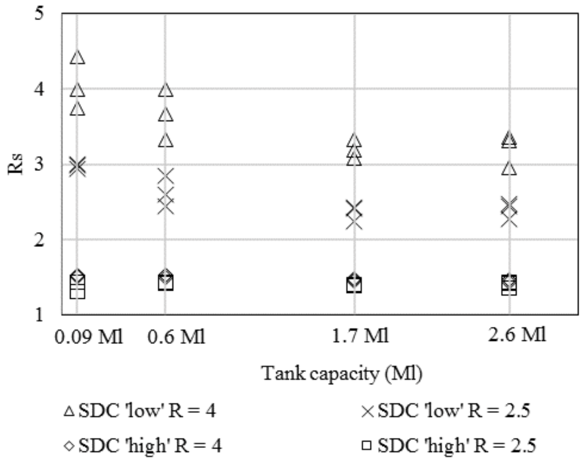


(b) Strength factor

Fig. 8 Effect of staging height on seismic response factors



(a) Ductility factor



(b) Strength factor

Fig. 9 Effect of tank size on seismic response factors

to soil layers have not been considered, which may further affect the analytically computed response reduction factors.

9. Conclusions

From past earthquakes it was observed that common failures of elevated water tanks were due to failure of staging. However, these water tanks are considered as important structures and an operational performance after earthquake is desired, no specific guidelines to limit thenonlinear roof drift as well as the level of allowed damage has been specified in the literature. The code specified seismic design is based on reducing the anticipated level of earthquake force by a single valued response reduction factor. Broadly, the response reduction factor can be decomposed into strength factor (includes the effect of redundancy) and ductility factor. In the present study RC elevated water tanks supported on frame staging is considered and designed for two response reduction factors i.e., R=2.5 and R=4 for ordinary moment resisting frame and special moment resisting frame detailed for improved ductility, respectively. A total of 48 models are developed considering the various combinations of tank capacity, staging height and seismicity. The design criteria and minimum cross section is decided on the basis of IS 1893 part 2 (2014). The key components of response

Table 5 Average seismic response factors for RC frame staging

	Tank size	SDC 'high'		SDC 'low'	
		R=2.5	R=4	R=2.5	R=4
R_s*	Small	1.4	1.5	3.0	4.1
	Medium	1.4	1.5	2.6	3.7
	Large	1.4	1.5	2.4	3.2
	Very large	1.4	1.5	2.4	3.2
R_μ	Small	2.7	3.7	1.6	1.6
	Medium	2.5	3.8	1.7	1.8
	Large	2.4	3.7	2.4	2.5
	Very large	2.4	3.7	2.1	2.2
R	Small	3.7	5.6	4.7	6.7
	Medium	3.6	5.7	4.5	6.5
	Large	3.4	5.4	5.6	7.9
	Very large	3.3	5.4	5.0	7.0

*R_s: Strength factor; R_μ: Ductility factor; R: Response reduction factor

reduction factor i.e., strength and ductility factor is obtained from nonlinear static pushover analysis.

For the models considered in the study it is observed that the strength and ductility factors are higher for the models designed for R=4 as compared to models designed for R=2.5. The progressive hinge formation pattern differs for models designed for R=2.5 and R=4. In case of model designed for R=4 the hinge formation in column starts after formation of hinges in several brace beams, whereas, in the model designed for R=2.5 the hinge in column starts after formation of hinges in few brace beams. This is also reflected from the ductility factor (R_μ) which is relatively more in models designed for R=4. With respect to change in staging height, it is observed that the maximum base shear decreases with the increase in staging height, however, its effect on strength factor is only marginal. This is due to the fact that with increase in staging height the fundamental period of structure increases leading to reduction in design base shear. In case of SDC 'high', the ductility factor increases with the increase in staging height, whereas, in case of SDC 'low', the ductility factor has a negligible effect on staging height, but the strength factor marginally decreases with the increase in staging height. With respect to change in tank capacity, it is observed that with the increase in tank capacity the initial slope of the pushover curves increases; however, the yield and the maximum displacements are almost constant. It is observed that for SDC 'high' the effect of increase in tank capacity is negligible on both R_s and R_μ. In contrary, for SDC 'low' the R_s decreases with increase in tank capacity, whereas, R_μ increases with the increase in tank capacity. The response reduction factor computed from the pushover analysis indicates that the consideration of R=2.5 for ordinary moment resisting frame and R=4 for special moment resisting frame is a reasonable approximation for SDC 'high'. However, for SDC 'low' the computed response reduction factor is higher than code specified response reduction factor. This may be attributed to the fact that the minimum section dimension specified in code is same for all seismic design categories, whereas, for SDC 'low' the required dimension of members from analysis are smaller. Therefore, it is suggested that the minimum dimension criteria can be varied with the level of seismicity. Moreover, the higher response reduction factor computed from nonlinear static pushover analysis has certain limitations in capturing the precise nonlinear response. Also, the effect of fluid-structure interaction, soil-structure interaction and ground motion amplification due to soil layers has not been considered, which may further affect the analytically computed response reduction factors. These issues require analytical and experimental studies, and the study can be further extended incorporating the aforementioned parameters to achieve more reasonable values of response reduction factor.

References

AlHamaydeh, M., Abdullah, S., Hamid, A. and Mustapha, A. (2011), "Seismic design factors for RC special moment resisting frames in Dubai, UAE", *Earthq. Eng. Eng. Vib.*, **10**(4), 495-506.

ASCE 41-06 (2007), Seismic Rehabilitation of Existing Buildings, American Society of Civil Engineers; Reston, Virginia, USA.

ASCE 41-13 (2014), Seismic Rehabilitation of Existing Buildings, American Society of Civil Engineers; Reston, Virginia, USA.

ASCE 7 (2010), Minimum design loads for buildings and other structures, American Society of Civil Engineers; Reston, Virginia, USA.

Astaneh, A. and Ashtiany, M.G. (1990), "The Manjil, Iran, earthquake of June 1990", Report No. 24(12); Earthquake Engineering Research Institute, California, USA.

ATC 19 (1995), Structural response modification factors, Applied Technology Council; Redwood City, California, USA.

ATC 40 (1996), Seismic evaluation and retrofit of concrete buildings, Applied Technology Council; Redwood City, California, USA.

Bertero, R.D. and Bertero, V.V. (1999), "Redundancy in earthquake-resistant design", *J. Struct. Eng.*, **125**, 81-88.

Chandrasekaran, A.R. and Krishna, J. (1954), "Water towers in seismic zones", *Proceedings of the Third World Conference Earthquake Engineering*, New Zealand, January.

Chaulagain, H., Rodrigues, H., Spacone, E. and Varum, H. (2015), "Seismic response of current RC buildings in Kathmandu Valley", *Struct. Eng. Mech.*, ***53***(4), 791-818.

Chaulagain, H., Rodrigues, H., Spacone, E., Guragain, R., Mallik, R. and Varum, H. (2014), "Response reduction factor of irregular RC buildings in Kathmandu valley", *Earthq. Eng. Eng. Vib.*, **13**(3), 455-470.

Chen, C.P. and Barber, R.B. (1976), "Seismic design of liquid storage tanks to earthquakes", *Proceedings of the International Symposium on Earthquake Structural Engineering*, St. Louis, Missouri, August.

Dutta, S., Mondal, A. and Dutta S.C. (2004), "Soil structure interaction in dynamic behaviour of elevated tanks with alternate frame staging configurations", *J Sound Vib*., **277,** 825-53.

Dutta, S.C., Dutta, S. and Roy, R. (2009), "Dynamic behavior of R/C elevated tanks with soil-structure interaction", *Eng. Struct*., **31**(11), 2617-2629.

Elnashai, A.S. and Mwafy, A.M. (2002), "Overstrength and force reduction factors of multistorey reinforced-concrete buildings", *Struct. Des. Tall Build.*, **11**(5), 329-351.

Eurocode 8 (2006), Design of Structures for Earthquake Resistance Part 4: Soils, Tanks and Pipelines, European Committee for Standardization, Brussels, Belgium.

Fajfar, P. and Krawinkler, H. (1992), *Nonlinear Seismic Analysis and Design of Reinforced Concrete Buildings*, Taylor and Francis, New York, USA.

Fanaie, N. and Dizaj, E.A. (2014), "Response modification factor of the frames braced with reduced yielding segment BRB", *Struct. Eng. Mech.*, **50**(1), 1-17.

FEMA 356 (2000), Commentary for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency; Washington, DC, USA.

FEMA P695 (2009), Quantification of Building Seismic Performance Factors, Federal Emergency Management Agency; Washington, DC, USA.

Ghateh, R., Kianoush, M.R. and Pogorzelski, W. (2015), "Seismic response factors of reinforced concrete pedestal in elevated water tanks", *Eng. Struct.*, **87**, 32-46.

Haroun, M.A. and Ellaithy, M.H. (1985), "Seismically induced fluid forces on elevated tanks", *J. Tech. Top. Civil Eng*., **111**, 1-15.

Haroun, M.A. and Housner, G.W. (1981), "Seismic design of liquid storage tanks", *ASCE J. Tech. Coun*., **107**(1), 191-207.

Housner, G.W. (1963), "The dynamic behavior of water tanks", *Bull. Seismol. Soc. Am.*, **53**(2), 381-387.

Humar, J.L. and Rahgozar, M.A. (1996), "Concept of overstrength in seismic design", *Proceedings of the 11th World Conference on Earthquake Engineering,* Acapulco, Mexico, June.

Husain, M. and Tsopelas, P. (2004), "Measures of structural redundancy in reinforced concrete buildings. I: Redundancy indices", *J. Struct. Eng*., **130**, 1651-1658.

IS 11682 (1985), Criteria for design of RCC staging for overhead water tanks, Bureau of Indian Standards; New Delhi, India.

IS 13920 (1993), Ductile detailing of reinforced concrete structures subjected to seismic forces-code of practice, Bureau of Indian Standards; New Delhi, India.

IS 1893 part 1 (2002), Criteria for earthquake resistant design of structures: part 1 general provisions and buildings, Bureau of Indian Standard, New Delhi, India.

IS 1893 part 2 (2014), Criteria for earthquake resistant design of structures part 2 liquid retaining tanks, Bureau of Indian Standards; New Delhi, India.

IS 456 (2000), Plain and reinforced concrete-code of practice, Bureau of Indian Standards, New Delhi, India.

Jain, S. K., Murty, C.V.R., Chandak, N., Seeber, L. and Jain, N.K. (1994), "The September 29, 1993, M6.4 Killari, Maharashtra Earthquake in Central India", Report No. 28(1); Earthquake Engineering Research Institute, California, USA.

Jain, S.K. and Navin, R. (1995), "Seismic overstrength in reinforced concrete frames", *J. Struct. Eng.*, **121**(3), 580-585.

Jaiswal, O.R., Rai, D.C. and Jain, S.K. (2007), "Review of seismic codes on liquid-containing tanks", *Earthq. Spectra*, **23**(1), 239-260.

Kadas, K. (2006), "Influence of idealized pushover curves on seismic response", M.Sc. Dissertation, Middle East Technical University, Ankara, Turkey

Kappos, A.J. (1999), "Evaluation of behaviour factors on the basis of ductility and overstrength studies", *Eng. Struct.*, **21**(9), 823-835.

Kim, J., Park, J. and Kim, S.D. (2009), "Seismic behavior factors of buckling-restrained braced frames", *Struct. Eng. Mech.*, **33**(3), 261-284.

Livaoglu, R. (2013), "Soil interaction effects on sloshing response of the elevated tanks", *Geomech. Eng.*, **5**(4), 283-297.

Livaoglu, R. and Dogangun, A. (2005), "Seismic evaluation of fluid-elevated tank-foundation/soil systems in frequency domain", *Struct. Eng. Mech*., **21**(1), 101-119.

Livaoglu, R. and Dogangun, A. (2006), "Simplified seismic analysis procedures for elevated tanks considering fluid-structure-soil interaction", *J. Fluid. Struct.*, **22**(3), 421-439.

Livaoglu, R. and Dogangun, A. (2007a), "Effect of foundation embedment on seismic behavior of elevated tanks considering fluid-structure-soil interaction", *Soil Dyn. Earthq. Eng.*, **27**(9), 855-863.

Livaoglu, R. and Dogangun, A. (2007b), "Seismic behaviour of cylindrical elevated tanks with a frame supporting system on various subsoil", *Ind. J. Eng. Mater. Sci.*, **14**, 133-145.

Malhotra, P.K., Wenk, T. and Weiland, M. (2000), "Simple procedure of seismic analysis of liquid-storage tanks", *J. Struct. Eng. Int.*, **10**(3), 197-201.

Masoudi, M., Eshghi, S. and Ghafory-Ashtiany, M. (2012), "Evaluation of response modification factor (R) of elevated concrete tanks", *Eng. Struct*., **39**, 199-209.

Massumi, A. and Mohammadi, R. (2016), "Structural redundancy of 3D RC frames under seismic excitations", *Struct. Eng. Mech.*, **59**(1), 15-36.

Mehrain, M. (1990), "Reconnaissance report on the Northern Iran earthquake of June 21, 1990", Research Report No. NCEER-90-0017; National Center for Earthquake Engineering Research, State University of New York at Buffalo, New York, USA.

Miranda, E. (1993), "Site-dependent strength-reduction factors", *J. Struct. Eng.*, **119**(12), 3503-3519.

Miranda, E. and Bertero, V.V. (1994), "Evaluation of strength reduction factors for earthquake-resistant design", *Earthq. Spectra*, **10**(2), 357-379.

Mitchell, D. and Paultre, P. (1994), "Ductility and overstrength in seismic design of reinforced concrete structures", *Can. J. Civil Eng.*, **21**(6), 1049-1060.

Mohammadi, R., Massumi, A. and Meshkat-Dini, A. (2015), "Structural reliability index versus behavior factor in RC frames with equal lateral resistance", *Earthq. Struct.*, **8**(5), 995-1016.

Mondal, A., Ghosh, S. and Reddy, G.R. (2013), "Performance-based evaluation of the response reduction factor for ductile RC frames", *Eng. Struct.*, **56**, 1808-1819.

Newmark, N.M. and Hall, W.J. (1982), *Earthquake Spectra and Design*, Earthquake Engineering Research Institute, Berkeley, California, USA.

Omidinasab, F. and Shakib, H. (2012), "Seismic response evaluation of the RC elevated water tank with fluid-structure interaction and earthquake ensemble", *KSCE J. Civil Eng.*, **16**(3), 366-376.

Ozmen, H.B. and Inel, M. (2008), "Evaluation of strength reduction factor for existing mid-rise RC buildings", *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Ozmen, H.B., Inel, M. and Meral, E. (2014), "Evaluation of the main parameters affecting seismic performance of the RC buildings", *Sadhana*, **39**(2), 437-450.

Park, R. (1988), "Ductility evaluation from laboratory and analytical testing", *Proceedings of the 9th world conference on earthquake engineering*, Tokyo-Kyoto, Japan, August.

Paulay, T. and Priestley, M.J.N. (1992), *Seismic Design of Reinforced Concrete and Masonry Buildings*, John Wiley & Sons, Inc.

Priestley, M.J.N. and Park, R. (1987). "Strength and ductility of concrete bridge columns under seismic loading", *ACI Struct. J.*, **84**(1), 61-76.

Rai, D.C. (2002), "Elevated tanks", *Earthq. Spectra*, **18**(S1), 279-295.

Rai, D.C. (2003), "Performance of elevated tanks in mw 7.7 bhuj earthquake of january 26th, 2001", *J. Earth Syst. Sci.*, **112**(3), 421-429.

Riddell, R. and Newmark, N. (1979), "Statistical analysis of the response of nonlinear systems subjected to earthquakes", Research Report No. 468; Department of Civil Engineering, University of Illinois, Urbana, USA.

Saffarini, H.S. (2000), "Ground motion characteristics of the november 1995 aqaba earthquake", *Eng. Struct.*, **22**(4), 343-351.

SAP2000 (2004), Integrated Software for Structural Analysis & Design. Computers and Structures Inc., Berkeley, California, USA.

Shakib, H., Omidinasab, F. and Ahmadi, M.T. (2010), "Seismic demand evaluation of elevated reinforced concrete water tanks", *Int. J. Civil Eng.*, **8**(3), 204-220.

Shepherd, R. (1972), "The two mass representation of a water tower structure", *J. Sound Vib.*, **23**(3), 391-396.

Sonobe, Y. and Nishikawa, T. (1969), "Study of the earthquake proof design of elevated water tanks", *Proceedings of the Fourth World Conference Earthquake Engineering*, Santiago, Chile, January.

Steinbrugge, K.V. and Flores, R. (1963), "The chilean earthquakes of May, 1960: a structural engineering viewpoint", *Bull. Seismol. Soc. Am.*, **53**(2), 225-307.

Stembrugge, K. and Clough, R.W. (1960), "Chilean Earthquakes of May, 1960: A Brief Trip Report", *Proceedings of the 2nd World Conference on Earthquake Engineering*, Tokyo and Kyoto, Japan, July.

Tsopelas, P. and Husain, M. (2004), "Measure of structural redundancy in reinforced concrete buildings. II: Redundancy response modification factor R_R", *J. Struct. Eng*., **130**, 1659-1666.

Veletsos, A.S. and Tang, Y. (1990), "Soil-structure effects for laterally excited liquid storage tanks", *Earthq. Eng. Struct. D*., **19**, 473-496.

Whittaker, A. and Rojahn, C. (1999), "Seismic response modification factors", *J. Struct. Eng*., **125**, 438-444.

CC