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Soil–structure interaction in dynamic behaviour of elevated tanks with alternate frame staging configurations

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Abstract

The frame stagings with a single row of columns placed along the periphery of a circle, are generally adopted for elevated water tanks to support the tank container. Apart from this usual staging configuration, some alternate configurations are also used in practice. These alternate configurations are made by adding few structural members to the usual configuration. These staging configurations are advantageous for adoption from a few different viewpoints. The present paper aims to observe the effect of soil–structure interaction on two dynamic characteristics namely, the impulsive lateral period which regulates lateral seismic behaviour and the impulsive torsional-to-lateral period ratio which regulates torsional vulnerability of the structure. The analytical expressions for these two dynamic characteristics have been derived considering the effect of soil-flexibility for elevated water tanks with these alternate configurations. These formulations have been validated against the results of finite element analysis for a few example tanks. A parametric study with limited example tanks based on these formulations shows that the frame staging with all kinds of alternate configurations having less panel heights, more number of columns, larger column diameter and stiffer circumferential beams compared to columns encounters the strongest influence of soil–structure interaction effect. The study on the example tanks with different alternate configurations shows that the design of elevated tanks based on a fixed base assumption may lead to wrong assessment of seismic base shear. The underestimation of base shear may lead to unsafe design whereas overestimation may cause uneconomic design. Neglecting soil-flexibility may also cause overlooking the possibility of occurring axial tension in columns and wrong assessment of torsional vulnerability of the staging structures.

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1. Introduction

The reinforced concrete frame type staging of elevated water tanks generally has vertical columns resting on the perimeter of a circle (as shown in Fig. 1). The columns are connected by circumferential beams at regular intervals. These circumferential beams divide the staging configuration into a number of panels. This type of staging configuration more frequently used in practice has been referred as basic configuration in the literature [1]. This type of staging configuration is extensively studied [2–4] considering soil-flexibility under ground excitation to

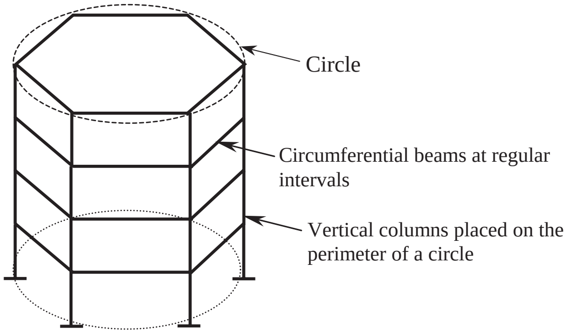
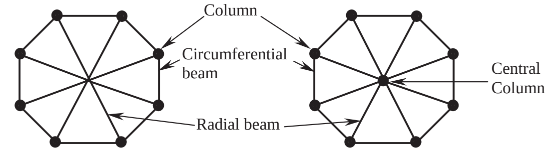
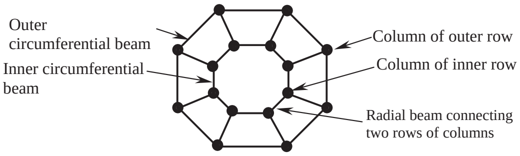


Fig. 1. Usual staging configuration.

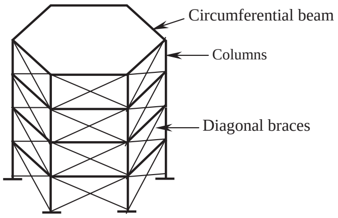


(a) **Plan of staging with radial beams**

(b) **Plan of staging with radial beams and a central column**



(c) **Plan of staging with two-concentric rows of columns connected by circumferential and radial beams**



(d) **Staging with diagonal braces**

Fig. 2. Alternate staging configurations.

assess their seismic vulnerability. Apart from this basic configuration of elevated water tanks, some alternate configurations as described in the literature [5] are also used in practice. These alternate configurations can be made by a little bit alterations of the basic configuration, by adding few more members to it. Four such configurations are made by adding to the usual configuration: (a) radial beams at the level of circumferential beams (Figs. 2a), (b) radial beams and a central column (Fig. 2b), (c) another concentric row of columns connected through radial and circumferential beams (Figs. 2c) and (d) steel diagonal braces (Fig. 2d). Adoption of these configurations may be advantageous in different aspects. These configurations involve large number of structural members as compared to the basic configuration. This causes an increase in redundancy of the structure. Hence, there may be better scope of re-distribution of forces in the post-elastic range and that may increase the possibility of survival of the structure with some damage avoiding collapse in case of a severe seismic ground shaking. In the fourth alternate staging configuration, the addition of steel diagonal braces may attribute an overall ductile nature in the post-elastic range behaviour of the structure because of ductile deformation capacity of steel diagonal braces. Apart from that, these alternate configurations can reduce torsional vulnerability of the elevated tank stagings by breaking the closeness of torsional and lateral natural periods. Frame stagings of elevated tanks are vulnerable under severe torsional vibration arising due to coupling with translational motion caused by accidental eccentricity if torsional-to-lateral period ratio, τ, of the structure lies within the critical range of 0.7–1.25 [1,6]. To keep the value of τ outside the critical range, the first three of the four alternate configurations may be adopted when τ is required to be increased and the fourth alternate configuration can be adopted when τ is required to be decreased [5].

In this context, the present study is an effort to gauge the effect of soil–structure interaction on dynamic characteristics and seismic response of these alternate staging configurations. To achieve this end, analytical formulations for lateral and torsional stiffness of these staging configurations are developed which helped to identify the influential parameters. Expressions for lateral and torsional natural periods are obtained from them. These analytical formulations are compared with the results of finite element analysis for a number of example tank problems and found to be accurate enough. A detailed and exhaustive parametric study is then conducted to see the extent of soil–structure interaction effect on these dynamic characteristic parameters, namely, impulsive lateral natural period and impulsive torsional-to-impulsive lateral period ratio.

Analytical formulations for lateral and torsional stiffnesses of the alternate configurations are available in the literature [5]. But, those formulations are based on the fixed base assumption for the staging columns. Actually, the supporting soil medium allows movement of the foundation to some extent resulting in subsequent increase in the lateral natural period. This increase in lateral period will result in a change in the spectral acceleration ordinate [7]. Accordingly the base shear will also change as base shear is directly proportional to spectral acceleration. Also, with fixed base assumption, wrongly assessed τ may lead to a wrong conclusion about the torsional vulnerability of elevated tanks. So, consideration of the effect of soil–structure interaction in the calculation of dynamic characteristics is extremely important from the view point of the seismic safety of the staging structures. The same aspects of the elevated tanks with usual staging configuration have already been studied in details in the literature [2–4].

2. Idealization of system

The structure and the soil have been idealized in a similar manner as that has been developed for usual staging configuration [2–4]. For finite element analysis, the tank container with a radius, R_c, is assumed to behave as a rigid cylindrical shell having maximum allowable water depth of H. Again, h denotes the depth of water at any instant of time. During lateral mode of vibration of the water tank, a part of the water moves in a long period sloshing motion, while the rest part moves rigidly with the tank wall. The former one is recognized as convective mass of water [8], while the latter part is known as impulsive mass of water. The impulsive mass of water experiences the same acceleration as the tank container and contributes predominantly to the base shear and overturning moment [8–10]. Thus, the behaviour of elevated tanks can be represented by an equivalent two-mass model as suggested in the literature [8]. For the sake of convenience, this two degrees of freedom system is schematically shown in Fig. 3a. The effective structural mass, M_s,

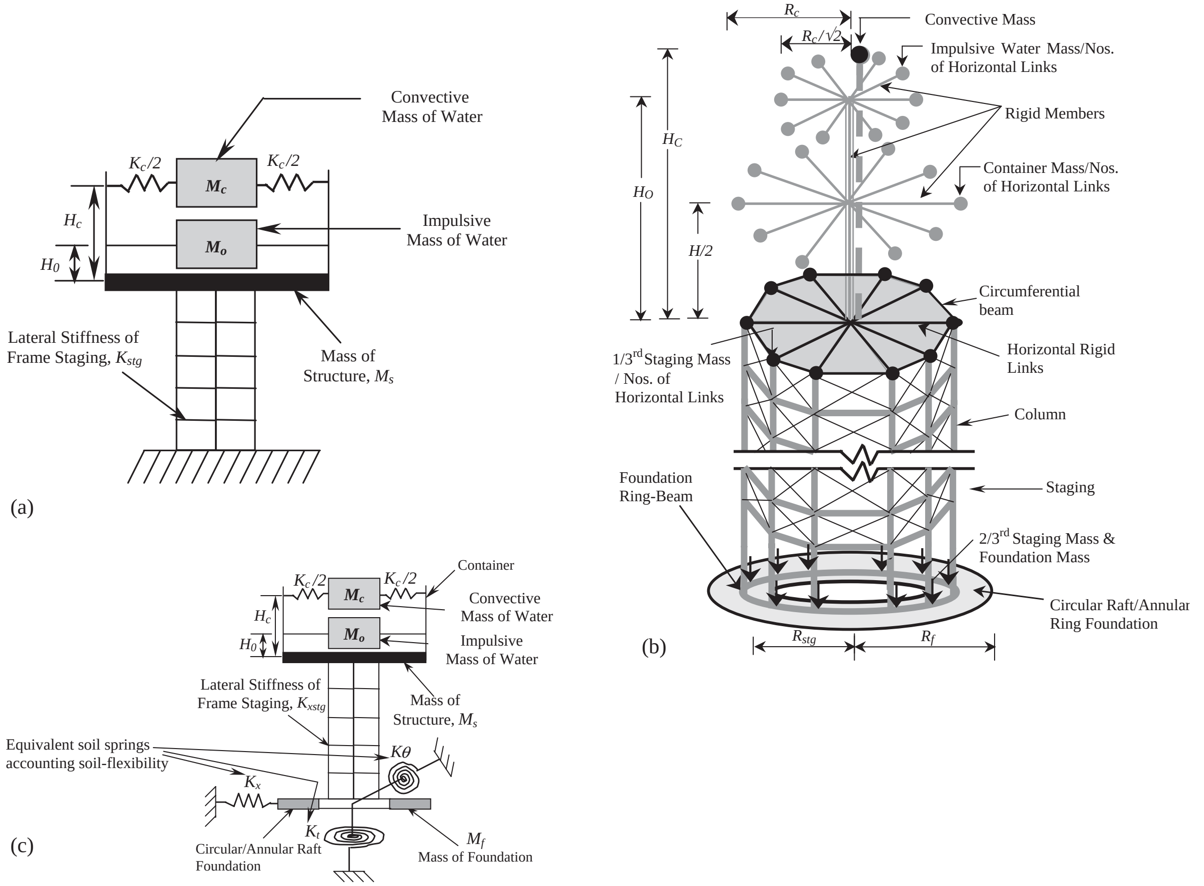


Fig. 3. (a) Two mass model for lateral vibration of typical elevated tank as proposed by Housner, 1963 [8]. (b) Idealized model showing distribution of container mass, staging mass, equivalent impulsive mass of water, equivalent convective mass of water and foundation mass. (c) Model for studying the effect of soil–structure interaction on lateral vibration of elevated tank.

i.e., the mass of the tank container and one-third mass of the staging [7,11] as well as the equivalent mass of water participating in impulsive mode, M_0, is considered to be rigidly attached to the tank container. The convective mass, M_c, is attached to the staging through a vertical member of height, H_c, attached at the top of staging level. The lateral stiffness, K_c, which is the equivalent stiffness involved in sloshing vibration is attached to M_c [8]. The expressions for these masses and stiffness quantities were originally proposed in a literature [8] and were finally reported further with minor modification in another literature [12]. The expressions for various equivalent mass and stiffness quantities according to the literature [12] are also given here for convenience of understanding:

$$M_0 = M\frac{\tanh(1.7R/h)}{1.7R/h}. \tag{1}$$

$$M_c = 0.71M\frac{\tanh(1.8h/R)}{1.8h/R}, \tag{2}$$

$$K_c = 4.75M_c^2\frac{gh}{MR^2}. \tag{3}$$

In these expressions, M denotes total mass of the water, R represents radius of container and g denotes acceleration due to gravity. The impulsive and convective masses are considered to be located at a height of H_0 and H_c, respectively, from the bottom of the tank container. The expressions for these heights according to the same literature [12] are as follows:

$$H_0 = \frac{3}{8}H\left\{1+\frac{4}{3}\left(\frac{M}{M_0}-1\right)\right\}, \tag{4}$$

$$H_c = H\left\{1-0.21\frac{M}{M_c}\left(\frac{R}{H}\right)^2+1.1\frac{R}{H}\sqrt{0.15\left(\frac{RM}{HM_c}\right)^2-1}\right\}. \tag{5}$$

The similar structural idealization and modelling were also considered in a recent study [13]. However, this study focused on investigating the seismic behaviour of base-isolated elevated tanks. The effect of soil-flexibility was not accounted in this literature [13]. On the other hand, the primary objective of the present investigation is to incorporate the effect of soil-flexibility in the dynamic and seismic bahaviour of elevated tanks with alternate frame staging configurations.

The various parts of the impulsive mass, namely, the mass contributed by staging, that contributed by impulsive mass of water and that contributed by container act at various heights. While considering the effect of soil–structure interaction, the rocking at the base of the staging is allowed. If the masses are not attached at the actual heights, the contribution of rocking may be erroneously evaluated. Hence, the various parts of the masses are attempted to be placed at right heights and location as described below.

At the top of the staging one-third mass of the staging following the guideline as indicated in Ref. [7] is equally distributed on each column for frame staging (Fig. 3b). At this level, rigid horizontal members radially connect the top nodal points of columns. From the central point where all these rigid horizontal links meet, a vertical rigid bar of height H_0 is connected. At the top of the bar, i.e., at height H_0, horizontal radially placed rigid members are provided with length equal to the radius of gyration $R_c/\sqrt{2}$ of water mass in the container. The impulsive water mass M_0 is equally distributed at the ends of these rigid members. Similarly, rigid horizontal members with length equal to the radius of container are provided at height $H/2$ from the top of the staging. The mass of the container is equally distributed at the ends of them. Two-third of the mass of the staging is equally distributed at the foundation level, at the radial distance of the staging radius. In finite element analysis the mass of the foundation is considered to be distributed over the circumference of a circle of radius equal to the radius of gyration of the circular raft foundation. In case of annular ring foundation, this circle coincides with the centre line of the annular ring foundation.

For calculation of torsional period, only the tank-empty condition is considered. It is conceived that almost the entire mass of water would participate in sloshing mode of vibration, which is physically intuitive [5,6]. Hence, for calculation of torsional period, the mass moment of inertia of empty tank container is considered and also used for tank-full condition.

Horizontal and vertical members of frame staging are modelled as two-noded frame elements in finite element analysis. The circular raft foundation is divided into 36 numbers of three noded plate elements and the structural deformation of the raft is minimized by using higher value of Young's modulus for the raft foundation, and thus, the idealization simulates to the rigid behaviour of raft. The foundation raft is supporting the staging and hence subjected to a distributed load near the periphery. Thus, there should be a tendency of deformation of the raft itself. Despite considering a higher value of Young's modulus for the circular raft foundation with the objective of attributing rigidity, the deformation of the raft is found to be changing with mesh sizes, though the value of the deformation is small. With the mesh sizes as mentioned above or mesh sizes smaller than this, the deformation at various points of the raft converges to stable minimum value. Thus, such a finer discretization in the foundation raft is used to obtain better accuracy.

The effect of soil–structure interaction on the dynamic behaviour of elevated water tank with considerably rigid foundation is studied using the idealization of a circular plate resting on semi-infinite homogeneous elastic half-space. The idealized model conceived on the basis of such consideration is illustrated in Fig. 3c. The stiffnesses of equivalent translational soil spring, K_x, equivalent rotational soil spring, K_θ, and equivalent torsional soil spring, K_t, to be attached below the central point of the rigid circular raft are taken from the literature [14]. The expressions suggested in this literature are based on a computational study [15] and its subsequent experimental verification [16].

The stiffnesses of the equivalent soil springs along horizontal translational degrees of freedom, K_x, along rocking degrees of freedom, K_θ, and along horizontal degrees of freedom, K_t, to be attached below the center of a rigid circular plate as per the literature [14], respectively, are as follows:

$$K_x = \frac{8Gr}{2 - v}, \tag{6}$$

$$K_\theta = \frac{8Gr^3}{3(1 - v)}, \tag{7}$$

$$K_t = 6Gr^3, \tag{8}$$

where r is the radius of the circular plate; G the shear modulus of the semi-infinite elastic soil medium; v the Poisson ratio of the same. In the above formulation of the stiffness quantities, radius of circular raft foundation (r) is considered as outer radius in case of annular ring foundation. A study [17] was made on the harmonic vibration of rigid and rough annular ring foundation on a homogeneous soil stratum. The results of the investigation show that the static torsional and rocking stiffness of an annular ring foundation can be considered as almost same as the corresponding stiffnesses of the circular raft foundation for values of the inner radius to outer radius ratio upto almost 0.75. Also, the horizontal and vertical stiffness of an annular ring foundation do not deviate from the corresponding stiffnesses of the circular raft foundation for inner-to-outer radius ratio upto almost 0.6. The ratio of outer and inner radii of the annular ring foundation is not generally exceeded by 0.6. Thus, the annular ring foundation can be considered as circular raft with radius equal to the outer radius of the ring foundation for calculating the stiffnesses of the equivalent soil springs.

It has been also observed that the stiffnesses of the equivalent soil springs are dependent on the frequency of the forcing function, i.e., ground excitation frequency particularly in case of long foundation resting on saturated clay [15]. In fact, the inertia force exerted by a time varying force imparts a frequency-dependent behaviour of the soil springs that seems to be more conveniently incorporated in stiffnesses in the equivalent sense [14]. Thus, the dependence of the stiffness of equivalent springs representing the deformable behaviour of soil is due to incorporation of the influence that frequency exerts on inertia. However, in general, purely stiffness properties are frequency independent. This frequency dependence of equivalent soil spring is incorporated by multiplying the equivalent spring stiffnesses by a frequency-dependent factor. This factor is plotted as a function of a non-dimensional parameter, a_0, where $a_0 = \omega B/V_s$, ω is the frequency of the forcing function, i.e., the frequency of ground excitation, B is the radius of the footing and V_s is the shear wave velocity in soil medium [14]. However, in case of earthquake motion, pulses with a wide range of frequencies generally participate together. So in such case, it appears to be very difficult to adopt any frequency-dependent factor in terms of the non-dimensional parameter, $a_0 = \omega B/V_s$. In fact, other literatures [18,19] have not recommended the use of such multiplication factors. Further, many studies [20,21] on the effect of soil–structure interaction on seismic behaviour of structures have not considered such factors perhaps due to the same reason. However, a limited example-based investigation has also been carried out on the effect of frequency-dependent multiplier in recent past following guidelines of the literatures [14,22] to study the behaviour of the tanks with usual configuration for two extreme values frequency-dependent multiplier a_0 ($= \omega B/V_s$), namely, 0.0 and 1.5. These results are not presented in the limited scope of the present paper. The dependence of the effect of soil–structure interaction on ground motion frequency is found to be marginal for seismic response of these structures. Hence, for the present study, this frequency-dependent multiplier has been taken to be 1.0 for all cases, which means that a frequency independent behaviour is considered.

The stiffnesses of the springs for various varieties of clayey soil has been obtained from values of shear modulus G of soil according to the empirical relationship, $G = 120N^{0.8}$ t/ft^2, as suggested in the literature [23]. The N represents the number of blows to be applied in Standard Penetration Test (SPT) of the soil. The Poisson ratio of soil has been taken as 0.5 for all the types of soil [24]. Following an established guideline [25] N is taken as 1, 3, 6, 12 and 22 for very soft, soft, medium, stiff and very stiff clay, respectively. Elevated water tanks both circular raft and annular ring type of foundations are considered in the scope of the present study. The sizes of the circular raft as well as annular ring foundations for various clayey soils are obtained thoroughly following the relevant Indian Standard Codes of practice [26,27].

3. Analytical expressions at fixed support condition

3.1. Alternate staging configuration with radial beams

Addition of radial beams at the level of circumferential beams (Fig. 2a) to the basic configuration will contribute to the lateral stiffness only whereas the torsional stiffness remains unchanged. The expressions of stiffnesses for this alternate configuration at fixed support condition as can be obtained from the literature [5] are given below. The lateral stiffness of the entire staging at fixed support condition is as follows:

$$K_{xstg} = \frac{12E_cI_cN_c}{h_p^3}\left[\frac{1}{N_p + 2(N_p-1)K_r/(1+0.5\,\delta_0\sin(\pi/N_c))}\right], \tag{9}$$

where E_c is the modulus of elasticity of the materials of columns, I_c the moment of inertia of column cross-section, N_c the number of columns, N_p the number of panels, h_p the height of each panel, K_r a stiffness related parameter which can be defined as the ratio of the flexural stiffness of columns and beams as given by $K_r = (E_cI_c/h_p)/(E_bI_b/l_b)$, where, l_b is the span of beam, E_b the modulus of elasticity of beam material, I_b the moment of inertia of beam cross-section, I_{br} the moment of inertia of radial beam cross-section, δ_0 the ratio of moments of inertia of radial and circumferential beams, I_{br}/I_b.

The expression of torsional stiffness at fixed support condition as given in the literature [1] is

$$K_{tstg} = \frac{12E_cI_cN_cR_{stg}^2}{h_p^3}\left[\frac{1}{N_p + (N_p-1)K_r/\cos^2(\pi/N_c)}\right], \tag{10}$$

where R_{stg} is the radius of staging.

3.2. Alternate staging configuration with radial beams and a central column

Addition of radial beam and a central column (Fig. 2b) will contribute to the stiffnesses in a similar way as in case of staging with radial beams, i.e., lateral stiffness will be increased and torsional will be unchanged from the basic configuration. The overall lateral stiffness of staging with radial beams and central column is given by

$$K_{xstg} = \frac{12E_cI_cN_c}{h_p^3}\left[\frac{1}{N_p + \dfrac{2(N_p-1)K_r}{1+\delta_0\sin(\pi/N_c)}} + \frac{\varphi}{N_pN_c + \dfrac{2(N_p-1)\varphi K_r}{\delta_0\sin(\pi/N_c)}}\right], \tag{11}$$

where φ is the ratio of the moments of inertia of central column to that of the circumferential columns, I_{cc}/I_c. I_{cc} and I_c are the moments of inertia of the central column, and that of the circumferential columns, respectively, $\delta_0 = I_{br}/I_b$ as mentioned earlier. N_c is the number of columns on the circular periphery of the staging, excluding the central column. Since, both the radial beams and the central column do not contribute any significant torsional stiffness, the expressions for torsional stiffness is same as given by Eq. (10) as in case of staging with radial beams.

3.3. Alternate staging configuration with two concentric rows of columns

Sometimes, two concentric rows of columns are provided and connected through radial and circumferential beams (Fig. 2c). At the inner row, equal numbers of columns, N_c, as at the outer row are provided, such that the staging has $2N_c$ number of columns in total. The inner row of columns contributes to both the lateral stiffness as well as torsional stiffness. The expressions of stiffnesses for this alternate configuration at fixed support condition as given in literature [5] are given below. Combining the stiffness terms due to outer and inner circular row of columns, the overall lateral staging stiffness, K_{xstg}, at fixed base condition, is given by

$$K_{xstg} = \frac{12E_cI_cN_c}{h_p^3}\left[\frac{1}{N_p + \dfrac{2(N_p-1)K_r}{1+\{\delta_0 \sin(\pi/N_c)/(1-\mu)\}}} + \frac{\eta}{N_p + \dfrac{2(N_p-1)\eta K_r}{(\delta_1/\mu)+\{\delta_0 \sin(\pi/N_c)/(1-\mu)\}}}\right]. \quad (12)$$

The overall torsional stiffness, K_{tstg} of the staging, at fixed base condition, is given by

$$K_{tstg} = \frac{12E_cI_cN_c}{h_p^3}\left[\frac{1}{N_p + \dfrac{(N_p-1)K_r}{\cos^2(\pi/N_c)}} + \frac{\eta\mu^2}{N_p + \dfrac{(N_p-1)\eta K_r\mu}{\delta_1 \cos^2(\pi/N_c)}}\right], \quad (13)$$

where μ is the ratio of radii of inner and outer concentric rows of columns, η the ratio of moment of inertia of columns in the inner and outer rows, δ_1 the ratio of moments of inertia of circumferential beams in the inner and outer circular staging frames.

3.4. Alternate staging configuration with diagonal braces

Sometimes diagonal steel braces are provided in the usual staging configuration. Diagonal braces induce truss action in the staging in addition to the existing frame action. Generally, two cross-braces are provided in each bay of each panel as shown in Fig. 2d. Under lateral load, one of them is in tension and the other in compression. The diagonal braces, which are under compression generally, have axial load larger than the buckling load and hence, their contributions are neglected. However, the present treatment can be easily extended to consider the contribution of both the diagonal braces. Provision of steel diagonal braces increases the ductility demand due to increase in redundancy of the structure during torsional vibration. According to literature [5], the lateral stiffness of staging with diagonal braces is

$$K_{xstg} = K_{fax} + K_{tax}, \quad (14)$$

where K_{fax} is the lateral stiffness due to frame action without considering the effect of diagonal braces and K_{tax} the lateral stiffness due to truss action:

$$K_{fax} = \frac{12E_cI_cN_c}{h_p^3}\left[\frac{1}{N_p + 2(N_p - 1)K_r}\right] \quad \text{and} \quad K_{tax} = \frac{(N_cA_0E_0/2N_pL_0)\cos^2\theta_v}{1 + C_1K_{arc} + C_2K_{arb}}.$$

A_0 is the area of cross-section of diagonal braces, E_0 the modulus of elasticity of diagonal braces, L_0 the length of diagonal braces, θ_v the angle of inclination of the diagonal braces with horizontal direction, K_{arc} the relative axial stiffness of diagonal braces with respect to that of columns, K_{arb} the relative axial stiffness of diagonal braces with respect to that of beams and can be expressed as $K_{arc} = (A_0E_0/L_0)/(A_cE_c/h_p)$ and $K_{arb} = (A_0E_0/L_0)/(A_bE_b/L_b)$. C_1 and C_2 are given by $C_1 = \{(4(N_p^2 - 1)/3)\sin^2(\pi/N_c) + 1\}\sin^2\theta_v$ and $C_2 = ((N_p - 1)/N_p)\cos^2\theta_v$.

Similarly, the torsional stiffness of staging with diagonal braces is

$$K_{tstg} = K_{fat} + K_{tat}, \tag{15}$$

where K_{fat} is the torsional stiffness due to frame action alone without considering the effect of diagonal braces and K_{tat} the torsional stiffness due to truss action alone. K_{fat} and K_{tat} can be expressed as

$$K_{fat} = \frac{12E_cI_cN_cR_{stg}^2}{h_p^3}\left[\frac{1}{N_p + (N_p - 1)K_r/\cos^2(\pi/N_c)}\right]$$

and

$$K_{tat} = \frac{\frac{A_0E_0}{L_0}N_cR_{stg}^2\cos^2\theta_v}{N_p\left[1 + K_{arc}\sin^2\theta_v + K_{arb}\frac{N_p - 1}{N_p}\cos^2\theta_v\right]}.$$

4. Analytical expressions considering soil-flexibility

The lateral stiffness of staging at fixed base condition, K_{xstg}, is considered to be connected in series with the equivalent translational soil spring of stiffness K_x and equivalent rotational soil spring of stiffness, K_θ. Thus, the equivalent lateral stiffness of the tank staging with the incorporation of the effect of soil-flexibility (K_{xeqv}) can be expressed as follows:

$$\frac{1}{K_{xeqv}} = \frac{1}{K_{xstg}} + \frac{1}{K_x} + \frac{L^2}{K_\theta}, \tag{16}$$

where L is the total height of the staging.

Similarly, the torsional stiffness of staging at fixed base condition (K_{tstg}) and torsional soil-spring, with stiffness, K_t, are considered to be connected in series to incorporate the effect of soil-flexibility. Hence, the analytical expression for equivalent torsional stiffness incorporating effect of soil-flexibility (K_{teqv}) can be obtained as

$$\frac{1}{K_{teqv}} = \frac{1}{K_{tstg}} + \frac{1}{K_t}. \tag{17}$$

From these staging stiffnesses, the impulsive lateral natural periods can be obtained by knowing the total impulsive mass of the elevated tank at tank-full as well as tank-empty condition. Hence, the ratio of impulsive lateral period considering soil–structure interaction, T_{ssi}, to that at fixed base condition, T_{fixed}, can be expressed in the following form:

$$\frac{T_{ssi}}{T_{fixed}} = \sqrt{\frac{K_{xstg}}{K_{xeqv}}} = \sqrt{K_{xstg}\left(\frac{1}{K_{xstg}} + \frac{1}{K_x} + \frac{L^2}{K_\theta}\right)}. \tag{18}$$

The torsional vulnerability of such elevated water tanks caused by lateral–torsional coupling arising out of accidental eccentricity is primarily regulated by the ratio of impulsive torsional to impulsive lateral periods, τ. The change in the value of this ratio (τ) due to the effect of soil–structure interaction can be well understood from the variation of the ratio τ_{ssi}/τ_{fixed}, where τ_{ssi} is the impulsive torsional-to-impulsive lateral period ratio considering soil-flexibility, while τ_{fixed} denotes impulsive torsional-to-impulsive lateral period ratio at fixed base condition. The ratio τ_{ssi}/τ_{fixed} can be expressed as follows:

$$\frac{\tau_{ssi}}{\tau_{fixed}} = \frac{\sqrt{K_{xeqv}/K_{teqv}}}{\sqrt{K_{xstg}/K_{tstg}}}. \tag{19}$$

5. Validity of performance of analytical formulations

To validate the performance of the analytical formulations, a large number of example elevated tanks are analyzed by using both analytical formulations and finite element method. The results of the formulations are found to be reasonably close as compared to the results of finite element analysis. The results of two example elevated water tanks with different alternate staging configurations are presented in the limited scope of this paper to prove the suitability of the analytical formulations for incorporating the effect of soil–structure interaction on dynamic characteristics of frame staging. The two example tanks are considered to be provided with two possible types of foundations namely circular raft and annular ring foundation. Various

Table 1
Details of structural configuration of containers of elevated tanks studied

Tank	Capacity of tank container (kl)	Aspect ratio		Mass of water in the container ($\times 10^3$ kg)
1	500	0.31	0.86	500.0
2	1500	0.33	0.61	1500.0

Table 2
Details of structural configuration of stagings of elevated tanks studied

Tank	Number of columns	Size of column (diameter) (mm)	Number of panels	Height of each panel (mm)	Staging radius (mm)	Size of circumferential beam (mm)
1	10	600	3	2500	3000	600 × 700
2	20	600	4	2500	6000	600 × 700

Table 3
Parameters used for clayey soils

Type of clay	N value	Shear modulus (kN/m^2)	Poisson ratio	Cohesion (kN/m^2)	Unit weight of saturated soil (kN/m^3)	Compression index	Initial void ratio
Very soft	1	12,900	0.5	9.80	13.5	0.279	1.20
Soft	3	31,066	0.5	18.5	17.0	0.189	0.90
Medium	6	54,089	0.5	36.8	18.5	0.135	0.72
Stiff	12	94,175	0.5	73.5	19.4	0.120	0.67
Very stiff	22	152,942	0.5	147.0	19.8	0.099	0.60

Table 4
Parameters of physical model

Tank	Mass of container ($\times 10^3$ kg)	Mass of staging ($\times 10^3$ kg)	Impulsive mass, M_0 ($\times 10^3$ kg)	Convective mass, M_c ($\times 10^3$ kg)	Convective spring stiffness, K_c (kN/m)
1	302.0	111.4	179.6	257.4	596.0
2	598.4	299.0	581.1	739.9	1284.0

categories of clayey soil are considered as supporting soil media. The details about the configurations of these example tanks are presented in Tables 1 and 2 for convenience of understanding. The sizes of the foundations have been obtained using different soil parameters are given in Table 3. The net safe bearing capacity as well as settlement criteria are considered as per relevant Indian codes [26,27] to calculate the sizes of the foundation. The soil-spring stiffnesses have been calculated according to the formulations presented in the literature [14]. Periods at fixed base condition and those considering soil-flexibility are calculated from free vibration analysis using the stiffnesses and the parameters as listed in Table 4.

The lateral and torsional stiffnesses of the example tank stagings have been calculated similarly by using analytical formulations for fixed base condition as well as flexible base condition. The lateral as well as torsional periods have been calculated from these stiffnesses. The effect of soil–structure interaction on the lateral natural period and torsional-to-lateral period ratio can be well manifested through the parameters T_{ssi}/T_{fixed}, i.e., the ratio of impulsive lateral periods with soil-flexibility to that with fixed base condition, and through τ_{ssi}/τ_{fixed}, i.e., the ratio of torsional-to-lateral period ratio considering soil-flexibility to that considering fixed base condition, respectively. T_{ssi}/T_{fixed} and τ_{ssi}/τ_{fixed} as obtained from finite element analysis and analytical formulations have been presented and compared in Tables 5 and 6, respectively, for stagings with circular raft and those with annular ring foundations. The results from the analytical formulations are found not to differ by more than about 5% from the results of finite element analysis. Hence, these analytical formulations are reliable to study the effect of soil–structure interaction on the dynamic characteristics of elevated tanks with frame type staging with alternate configurations. In the present investigation, hence, these analytical formulations have been used to observe the effects of soil–structure interaction on lateral natural period as well as on torsional-to-lateral period ratio for various alternate staging configurations. The significant influential parameters are first

Table 5
Comparison of results obtained from finite element analysis and analytical formulations for Tanks 1 and 2 (staging with circular raft foundation)

Alternate configuration	Type of clay	T_{ssi}/T_{fixed}		% deviation	τ_{ssi}/τ_{fixed}		% deviation
		Finite element	Analytical formula		Finite element	Analytical formula	
Tank 1							
With radial beams	Very soft	1.411	1.433	1.56	0.737	0.726	−1.49
	Medium	1.368	1.377	0.66	0.771	0.766	−0.65
	Very stiff	1.280	1.266	−1.09	0.813	0.823	1.23
With radial beams and central column	Very soft	1.528	1.489	−2.55	0.681	0.699	2.64
	Medium	1.475	1.426	−3.32	0.715	0.740	3.50
	Very stiff	1.339	1.302	−2.76	0.776	0.80	3.09
With two concentric rows of columns	Very soft	1.805	1.828	1.27	0.583	0.577	−1.03
	Medium	1.765	1.728	−2.10	0.606	0.621	2.48
	Very stiff	1.570	1.533	−2.36	0.671	0.688	2.53
With diagonal braces	Very soft	1.481	1.506	1.69	0.720	0.703	−2.36
	Medium	1.422	1.443	1.48	0.764	0.746	−2.36
	Very stiff	1.304	1.313	0.69	0.819	0.807	−1.47
Tank 2							
With radial beams	Very soft	1.390	1.436	3.31	0.786	0.762	−3.05
	Medium	1.265	1.250	−1.19	0.847	0.859	1.42
	Very stiff	1.136	1.130	−0.53	0.916	0.921	0.55
With radial beams and central column	Very soft	1.438	1.465	1.88	0.759	0.746	−1.71
	Medium	1.296	1.269	−2.08	0.826	0.846	2.42
	Very stiff	1.154	1.141	−1.13	0.902	0.913	1.22
With two concentric rows of columns	Very soft	1.793	1.834	2.29	0.645	0.611	−5.27
	Medium	1.490	1.502	0.81	0.758	0.728	−3.96
	Very stiff	1.260	1.276	1.27	0.868	0.826	−4.84
With diagonal braces	Very soft	1.518	1.518	0.0	0.752	0.748	−0.53
	Medium	1.342	1.302	−2.98	0.827	0.848	2.54
	Very stiff	1.209	1.159	−4.14	0.881	0.914	3.75

identified from analytical formulations. Then, each of the significant parameter involved in the analytical expressions is varied within a feasible range so that all possible configurations arising out of the combinations of all these parameters can be covered in the present research effort.

6. Variation of parameters

The effect of soil–structure interaction on lateral period and torsional-to-lateral period ratio of elevated water tanks has been analyzed for possible alternate staging configurations by varying

Table 6
Comparison of results obtained from finite element analysis and analytical formulations for Tanks 1 and 2 (staging with annular ring foundation)

Alternate configuration	Type of clay	T_{ssi}/T_{fixed}		% deviation	τ_{ssi}/τ_{fixed}		% deviation
		Finite element	Analytical formula		Finite element	Analytical formula	
Tank 1							
With radial beams	Very soft	1.395	1.413	1.29	0.743	0.735	−1.10
	Medium	1.316	1.312	−0.30	0.791	0.795	0.51
	Very stiff	1.221	1.190	−2.54	0.841	0.863	2.62
With radial beams with central column	Very soft	1.508	1.464	−2.92	0.690	0.710	2.90
	Medium	1.413	1.353	−4.25	0.739	0.770	4.19
	Very stiff	1.262	1.217	−3.57	0.816	0.845	3.55
With two concentric rows of columns	Very soft	1.795	1.793	−0.11	0.584	0.586	0.34
	Medium	1.630	1.609	−1.29	0.646	0.656	1.55
	Very stiff	1.372	1.391	−1.38	0.753	0.746	−0.93
With diagonal braces	Very soft	1.459	1.483	1.64	0.728	0.710	−2.47
	Medium	1.352	1.365	0.96	0.790	0.776	−1.77
	Very stiff	1.223	1.226	0.25	0.857	0.847	−1.17
Tank 2							
With radial beams	Very soft	1.350	1.376	1.93	0.793	0.781	−1.51
	Medium	1.212	1.175	−3.05	0.861	0.889	3.25
	Very stiff	1.104	1.079	−2.26	0.927	0.948	2.27
With radial beams and central column	Very soft	1.393	1.405	0.86	0.769	0.765	−0.52
	Medium	1.213	1.188	−2.06	0.860	0.880	2.33
	Very stiff	1.053	1.087	3.23	0.973	0.940	−3.39
With two concentric rows of columns	Very soft	1.689	1.730	2.43	0.661	0.633	−4.24
	Medium	1.356	1.357	0.07	0.807	0.779	−3.47
	Very stiff	1.178	1.170	−0.68	0.906	0.880	−2.87
With diagonal braces	Very soft	1.503	1.446	−3.79	0.739	0.764	3.38
	Medium	1.238	1.209	−2.34	0.863	0.878	1.74
	Very stiff	1.117	1.095	−1.97	0.929	0.941	1.29

different parameters as done in case of usual staging configuration. Number of columns for different type of tanks has been varied from 4 to 20 while number of panels are varied from 4 to 8. The minimum panel height has been chosen as 2.5 m whereas the maximum is taken as 5.0 m. The minimum and maximum staging radius have been considered as 3.0 and as 6.0 m, respectively. For the tanks with minimum staging radius (i.e., 3.0 m), number of columns has been varied from 4 to 10. On the other hand, the tanks with 6.0 m staging radius are analyzed with 8–20 number of columns. The flexural rigidity of beams and columns may be different for such type structures. So, the stiffness related parameter K_r may vary for different configurations. Thus, in the present study, three values of K_r, namely, 0.25, 1.0 and 4.0, have been taken. The results are presented for the stagings with two different column diameter of 400 and 600 mm, respectively. For the sake of brevity, cases involving other values of column diameter are not presented here. The analysis has been carried out considering very soft, soft, medium, stiff and very stiff clay as subgrade medium.

In case of alternate staging configuration with radial beams, δ_0 ($= I_{br}/I_b$) is considered to be equal to 1.0, i.e., the radial beam having the same cross-sectional dimensions of that circumferential beams. For staging with radial beams and central column, φ ($= I_{cc}/I_c$)) and δ_0 ($= I_{br}/I_b$) are considered to be 1.0, i.e., the cross-sectional dimensions of circumferential columns and central column are same and also the radial beams have the same cross-sectional dimensions as that of circumferential beams. For staging with two concentric rows of columns, the columns in inner and outer row are considered to have same cross-section and same material, i.e., $\eta = 1.0$ and $\delta_1 = 1.0$. The ratio of staging radius of inner row of columns to that of outer row of columns, μ, are considered to be 0.5. For staging with diagonal braces the diagonal members are made of steel rod of circular cross-section having diameter 50 mm.

7. Soil–structure interaction effect on dynamic characteristics

The effects of soil–structure interaction on lateral natural period and on torsional-to-lateral period ratio have been analysed with the help of the analytical formulations by varying all the parameters related to the structural configuration. For limited scope, few such trend-indicating cases are presented graphically in Figs. 4–8. The ratio of lateral period considering soil–structure interaction, T_{ssi}, to that in fixed support condition, T_{fixed}, and the ratio of the torsional-to-lateral period ratio considering soil–structure interaction, τ_{ssi}, to that in fixed support condition, τ_{fixed}, have been plotted against numbers of columns, N_c, in a single circular row for various numbers of panels for the alternate staging configurations in Figs. 4, 6, 7 and 8, respectively. For the sake of brevity, the curves for the staging configurations with $R_{stg} = 3.0$ m and $h_p = 2.5$ m resting on circular raft foundation on very soft clay are only presented in the paper. Further, the effect of softness of soil, the radius of staging, height of panel and relative flexural stiffness of columns with respect to that of beams may strongly affect the influence of soil–structure interaction on impulsive lateral period and impulsive torsional-to-lateral period ratio. To exhibit the nature of influence of these four parameters, T_{ssi}/T_{fixed} and τ_{ssi}/τ_{fixed} are also plotted as a function of N values of soil, radius of staging, height of panel and relative flexural stiffness of columns with respect to that of beams in Fig. 5 for alternate staging configuration with radial beam. The similar plots for other three configurations are also studied. Since, they exhibit almost similar tends, they are not presented in the paper for the sake of brevity. Thus, Figs. 4 and 5 present the results for alternate configuration with radial beams. The results for alternate configuration with radial beam and central column has been presented in Fig. 6. Similarly, for the third alternate staging configuration, i.e., staging with two concentric rows of columns, the effect of soil–structure interaction on dynamic characteristics has been shown in Fig. 7. The same for alternate configuration with diagonal braces are presented in Fig. 8.

The ratio T_{ssi}/T_{fixed} is always greater than 1.0 whereas the ratio τ_{ssi}/τ_{fixed} is always less than 1.0. This implies that effect of soil-flexibility increases the impulsive lateral period where as reduces the impulsive torsional-to-impulsive lateral period ratio, τ. In both the cases, it has been found that the changes due to soil–structure interaction are more effective in case of smaller panel height. The

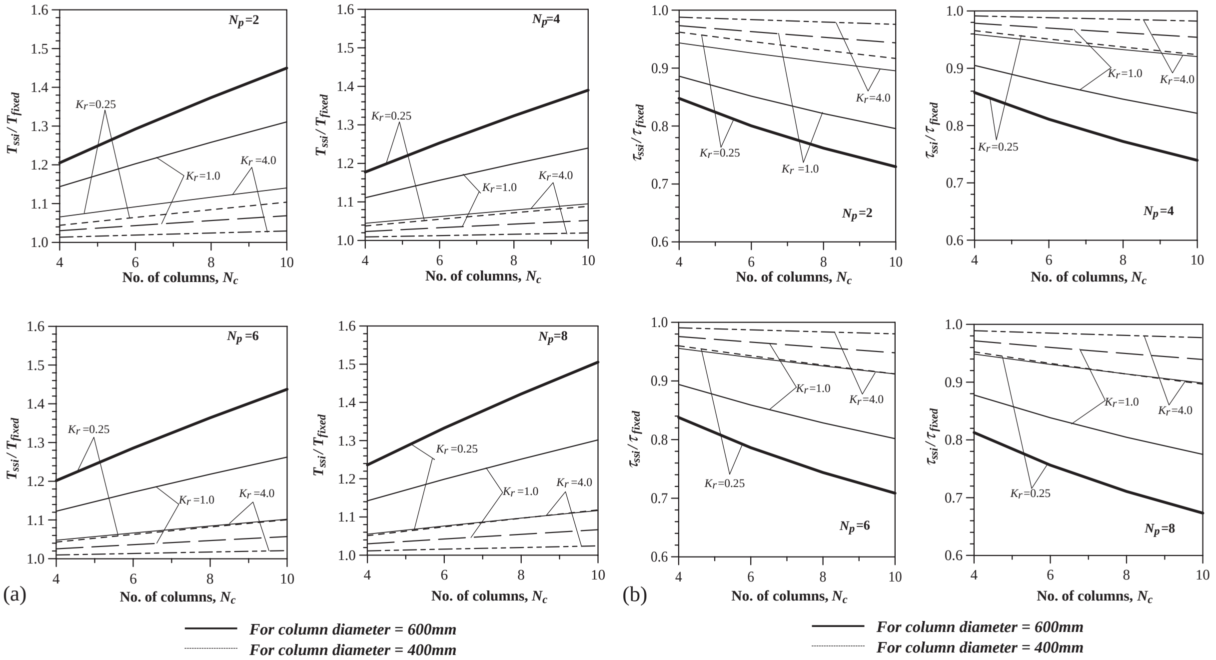
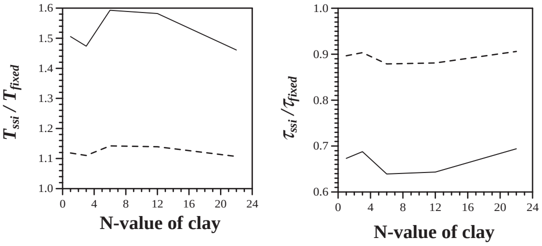


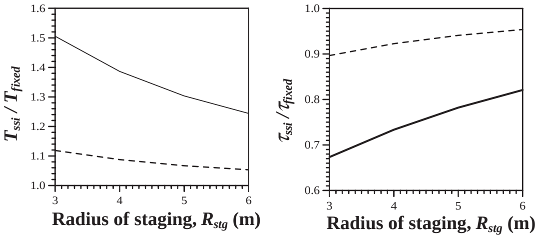
Fig. 4. (a) Effect of soil–structure interaction on T_{ssi}/T_{fixed} for alternate tank staging with radial beams resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0\,\text{m}$ and height of staging panel $h_p = 2.5\,\text{m}$. (b) Effect of soil–structure interaction on τ_{ssi}/τ_{fixed} for alternate tank staging with radial beams resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0\,\text{m}$ and height of staging panel $h_p = 2.5\,\text{m}$.

changes are very large in case of columns with 600 mm diameter whereas the changes are not so large in case of columns with 400 mm diameter. So, it is seen that column diameter is an important factor for regulating the effect of soil–structure interaction. Fig. 5 clearly indicates that the effect of soil–structure interaction is very strong particularly for frame staging with smaller panel height, larger number of columns, larger column diameter and circumferential beams stiffer than columns and of course, for softer soil. For the first alternate staging (i.e., the staging having radial beams) with circular raft resting on very soft clay, maximum increase in lateral period is about 51% (Fig. 4a) and maximum decrease in τ is about 33% (Fig. 4b). Similarly, in case of staging with radial beams and central column, maximum increase in lateral natural period is about 57% (Fig. 6a) and maximum decrease in τ is about 35% (Fig. 6b). For the third alternate staging configuration, i.e., staging with two concentric rows of columns, the effect of soil–structure interaction is quite large for both the dynamic characteristics. For this configuration maximum increase in lateral period is about 97% (Fig. 7a) and maximum decrease in τ is about 50% (Fig. 7b). These changes may have significant effect in lateral seismic response and in assessing torsional vulnerability. For alternate staging configuration with diagonal braces, maximum increase in lateral period is about 58% (Fig. 8a) and maximum decrease in τ is about 35% (Fig. 8b).

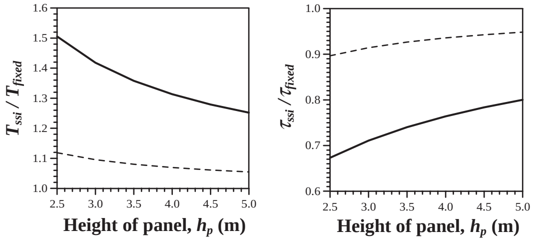
Fig. 5 for alternate staging configuration with radial beams indicate that the rates of change in T_{ssi}/T_{fixed} and τ_{ssi}/τ_{fixed} are higher when radius of staging, height of panel and relative flexural



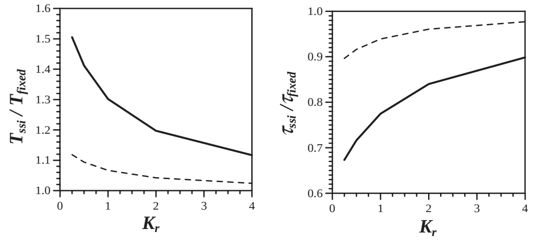
(a) **Tank with N_c=10, N_p=8, R_{stg}=3.0m, h_p=2.5m, K_r=0.25.**



(b) **Tank with N_c=10, N_p=8, h_p=2.5m, K_r=0.25 on very soft clay.**



(c) **Tank with N_c=10, N_p=8, R_{stg}=3.0m, K_r=0.25 on very soft clay.**



(d) **Tank with N_c=10, N_p=8, R_{stg}=3.0m, h_p=2.5m on very soft clay.**

——— ***For column diameter = 600mm***
- - - - - - ***For column diameter = 400mm***

Fig. 5. Effect of soil–structure interaction on two dynamic characteristics as a function of (a) N value of clay, (b) radius of staging, (c) height of panel and (d) K_r value for alternate tank staging with radial beams resting on circular raft foundation.

stiffness of columns with respect to that of beam are small. These rates of change decrease with increase in the value of each of them and finally exhibit a saturating trend for large values of each of these parameters. As mentioned earlier, the results for other three alternate staging configurations show similar trend as observed in case of alternate staging configuration with

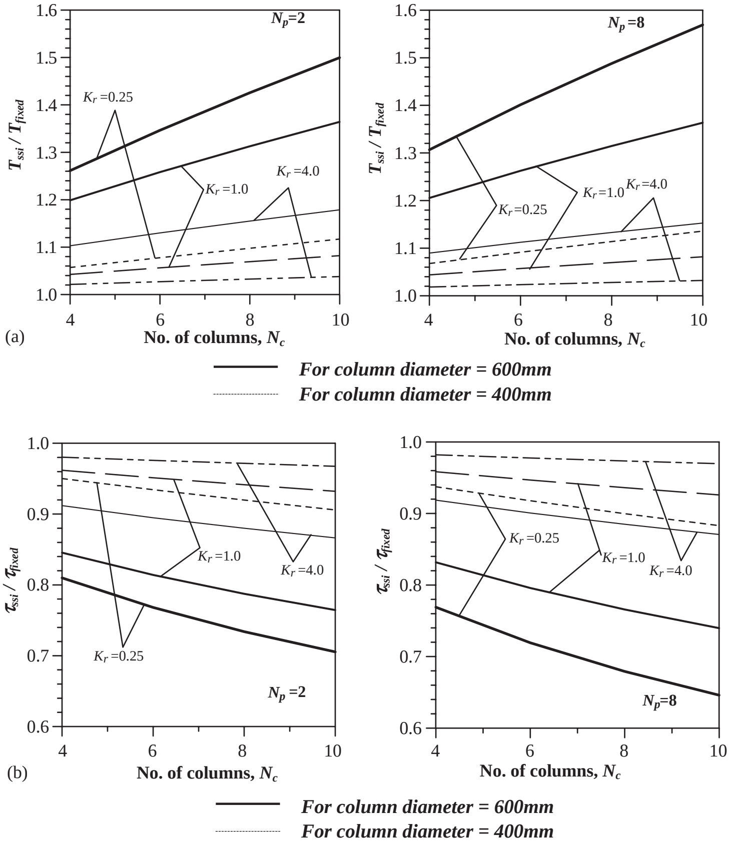


Fig. 6. (a) Effect of soil–structure interaction on T_{ssi}/T_{fixed} for alternate tank staging with radial beams and central column resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0\,\text{m}$ and height of staging panel $h_p = 2.5\,\text{m}$. (b) Effect of soil–structure interaction on τ_{ssi}/τ_{fixed} for alternate tank staging with radial beams and central column resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0\,\text{m}$ and height of staging panel $h_p = 2.5\,\text{m}$.

radial beams and hence not shown here for the sake of brevity. The effects seem to be maximized for medium clay. In fact, shear modulus decreases with softness of clay and sizes of foundation increases with the same. The stiffness of equivalent soil-springs decreases with decrease in shear modulus and increases with sizes of foundation. As a result of the two contradictory effects perhaps the spring stiffness minimizes in case of medium clay.

Staging with two concentric rows of columns may be used to increase the torsional-to-lateral period ratio while that with diagonal braces may be used to decrease the same, if the period ratio is within the critical range. They are also popular for their higher redundancy. These are the staging configurations which are more strongly influenced due to soil–structure interaction, as compared to the other two configurations. While choosing any of them, the considerable effect of soil–structure interaction on impulsive lateral period and impulsive torsional-to-impulsive lateral period ratio must be considered to avoid error in deriving these seismic characteristics.

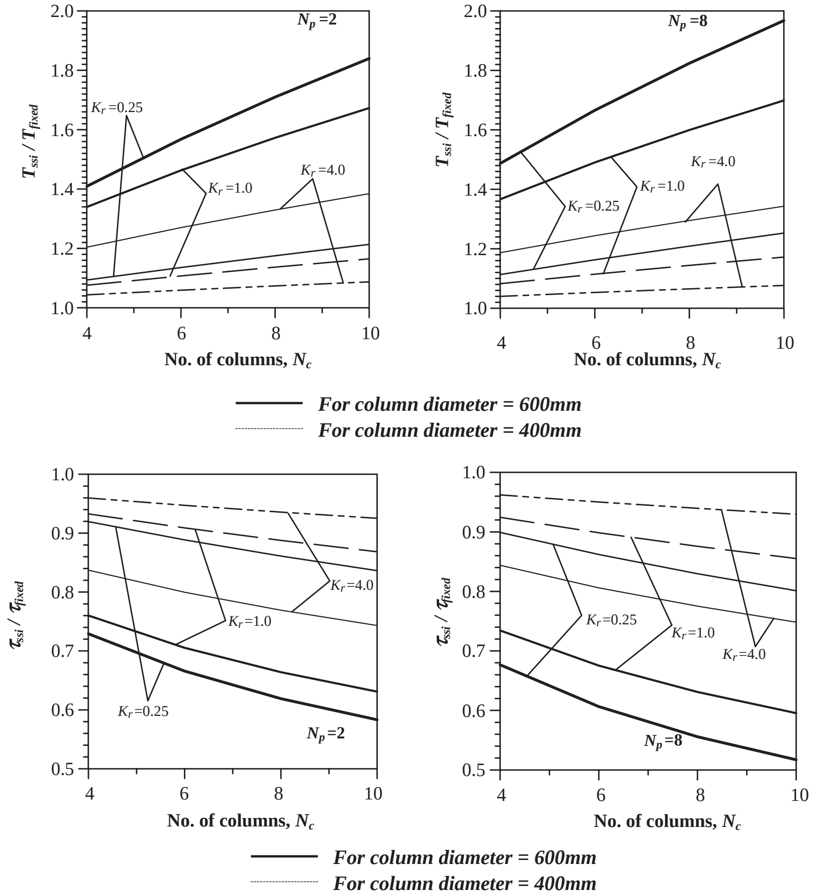


Fig. 7. (a) Effect of soil–structure interaction on T_{ssi}/T_{fixed} for alternate tank staging with two concentric rows of columns resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0$ m and height of staging panel $h_p = 2.5$ m. (b) Effect of soil–structure interaction on τ_{ssi}/τ_{fixed} for alternate tank staging with two concentric rows of columns resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0$ m and height of staging panel $h_p = 2.5$ m.

The analytical formulations or the variation curves presented here can be used as useful tools for evaluating the lateral period as well as impulsive torsional-to-impulsive lateral period ratio incorporating soil–structure interaction, for the purpose of practical design. The elevated tanks with alternate staging configurations resting on annular foundation are also studied but found to exhibit similar effect of soil–structure interaction regarding trends as well as order of magnitudes. Hence, the results for the same are not presented for the sake of brevity.

8. Effect of soil–structure interaction on lateral seismic response

To analyze the effect of soil–structure interaction on seismic response, the same two example tanks, the details of which are provided in Tables 1 and 2, are considered. The two tanks are of

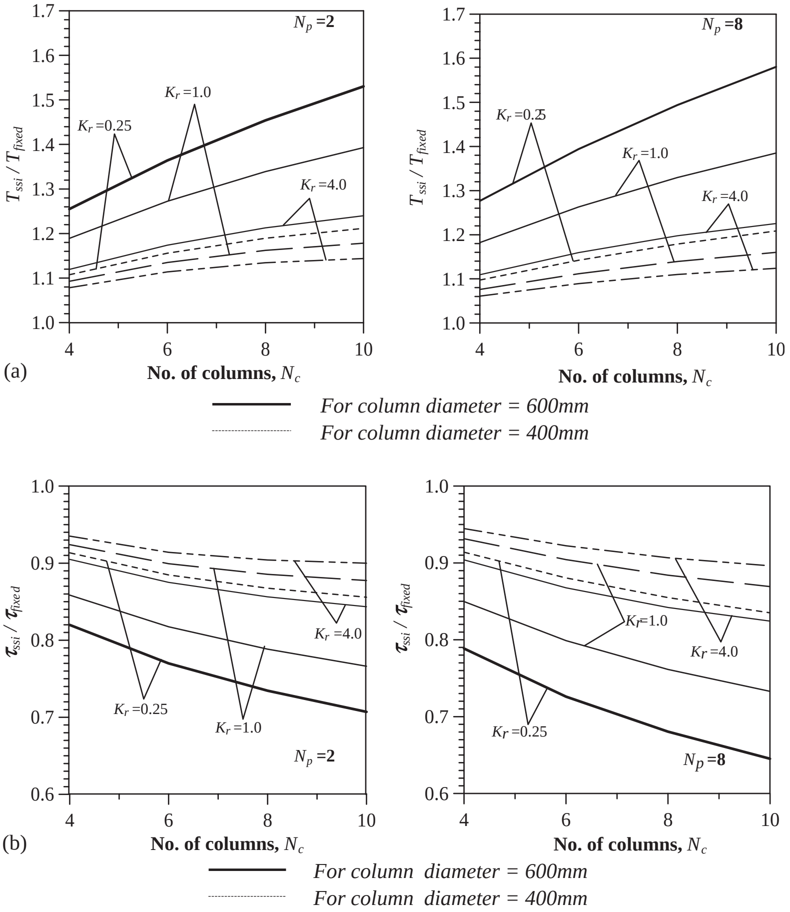


Fig. 8. (a) Effect of soil–structure interaction on T_{ssi}/T_{fixed} for alternate tank staging with diagonal braces resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0$ m and height of staging panel $h_p = 2.5$ m. (b) Effect of soil–structure interaction on τ_{ssi}/τ_{fixed} for alternate tank staging with diagonal braces resting on circular raft foundation on very soft clay, with radius of staging $R_{stg} = 3.0$ m and height of staging panel $h_p = 2.5$ m.

aspect ratio 0.31 and 0.33, respectively. The seismic base shear and maximum column forces of these two example tanks are obtained using the design spectrum (Fig. 9) corresponding to 5% of critical damping provided in 'Indian standard criteria for earthquake resistant design of structures' [28] considering fixed base condition and also considering the effect of soil-flexibility, as depicted earlier. The seismic base shear is also calculated for the above-mentioned two tanks having different aspect ratio. For Tank 1 and Tank 2, the changed aspect ratios are considered as 0.86 and 0.61, respectively, with the capacities remaining unchanged.

The contributions of different vibration modes to the base shear are combined by the well established Complete Quadratic Combination (CQC) method to obtain the seismic base shear. The method is used to obtain the contribution of the modes with close-spaced natural frequencies

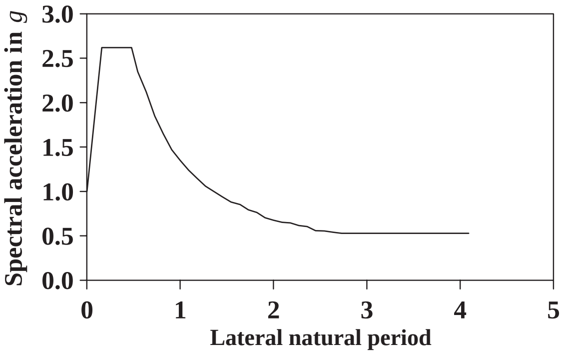


Fig. 9. Seismic design spectrum corresponding to 5% critical damping (IS: 1893–2000).

with reasonable accuracy. If the modal response be denoted by r_0, then according to CQC rule,

$$r_0 \cong \left(\sum_{i=1}^{N} \sum_{n=1}^{N} \rho_{in} r_{i0} r_{n0} \right)^{1/2} \tag{20}$$

where r_{i0} and r_{n0} are the peak responses corresponding to ith and nth mode, respectively, and ρ_{in} is the correlation coefficient between these two modes. ρ_{in} varies between 0 and 1 and $\rho_{in} = 1$ for $i = n$. Thus Eq. (20) can be further simplified in the following form:

$$r_0 \cong \left(\sum_{i=1}^{N} r_{n0}^2 + \sum_{i=1}^{N} \sum_{n=1}^{N} \rho_{in} r_{i0} r_{n0} \right)^{1/2}, \quad i \neq n. \tag{21}$$

This modal contribution combination method is applicable for wide variety of structures and the expressions for combined modal response depicted in Eqs. (20) and (21), are available in an well accepted literature [29]. The three-dimensional idealized model of elevated water tank as shown in Fig. 3b and described previously, is used for obtaining seismic response.

Consideration of 5% of critical damping is reasonable for dynamic analysis of concrete structures. It is observed from calculated soil damping following the guidelines as outlined in the literature [14,22] accounting for both radiation and material damping that, for an isolated raft and equivalent soil-spring system, the damping is not considerably larger than 5% for a wide range of shallow foundation with embedment lesser than half of the lateral dimension. This observation is also in line with the findings of an experiment as well as computation based study [30]. Moreover, this extent of damping will be further reduced if the effect is considered with respect to the entire structure-foundation-equivalent soil spring system, instead of considering isolated footing-equivalent soil-spring system. Thus, in absence of proper guidelines, 5% of critical damping in each mode was considered in the present investigation irrespective of the fixed base condition or support-flexibility.

Finally the base shear is arrived at following the provisions of Indian Earthquake Code [28] as well as a recent study [31] by applying seismic zone factor 0.36 for very severe seismic intensity, reduction factor 3.0 for ordinary moment-resisting frame and importance factor 1.5 prescribed for this type of life-line structures. Table 7 presents the base shear at fixed base condition and that considering soil-flexibility at both tank-full as well as tank-empty conditions for Tank 1 having an

Table 7
Change in seismic base shear due to the effect of soil–structure interaction for Tanks 1 and 2 at tank full and tank empty conditions

Alternate configuration	Type of clay	Seismic Base Shear (kN)					
		Tank full condition			Tank empty condition		
		Without *ssi*	With *ssi*	% change	Without *ssi*	With *ssi*	% change
Tank 1 (aspect ratio = 0.31)							
With radial beams	Very soft	1168.9	1365.9	16.85	746.6	960.2	28.61
	Medium		1145.2	−2.03		782.7	4.84
	Very stiff		1150.7	−1.56		757.2	1.42
With radial beams and central column	Very soft	1168.9	1372.4	17.41	746.1	963.9	29.19
	Medium		1143.0	−2.22		783.7	5.04
	Very stiff		1148.6	−1.74		756.9	1.45
With two concentric rows of columns	Very soft	1168.2	1386.4	18.68	744.1	961.9	29.27
	Medium		1194.8	2.27		787.1	5.78
	Very stiff		1165.7	−0.21		754.4	1.38
With diagonal braces	Very soft	1168.9	1388.8	18.81	745.5	966.4	29.63
	Medium		1145.0	−2.04		785.0	5.30
	Very stiff		1148.6	−1.74		756.3	1.45
Tank 2 (aspect ratio = 0.33)							
With radial beams	Very soft	3400.7	3066.1	−9.84	2041.0	2541.0	24.50
	Medium		3138.1	−7.72		2150.7	5.37
	Very stiff		3365.5	−1.04		1969.4	−3.51
With radial beams and central column	Very soft	3402.8	3119.4	−8.33	2040.7	2548.8	24.90
	Medium		3218.9	−5.40		2154.3	5.57
	Very stiff		3366.0	−1.08		2083.0	2.07
With two concentric rows of columns	Very soft	3410.3	3674.6	7.75	2037.4	2536.3	24.49
	Medium		3472.3	1.82		2155.8	5.81
	Very stiff		3411.4	0.03		2078.2	2.00
With diagonal braces	Very soft	3407.4	3095.8	−9.14	2039.5	2554.6	25.26
	Medium		3330.3	−2.26		2160.6	5.94
	Very stiff		3360.0	−1.39		2086.1	2.28

aspect ratio 0.31 and for Tank 2 having an aspect ratio of 0.33. The percentage change in base shear due to the effect of soil-flexibility is also presented in the same table. The table shows that the base shear may considerably increase (even to the extent of about 30%) due to the effect of soil–structure interaction in both tank-full as well as in tank-empty conditions. This effect is more pronounced in tank-empty condition for most of the cases.

In Table 8, the maximum column axial force, bending moment and shear force of Tank 1 are presented at fixed base condition and that considering soil-flexibility, at both tank-full and

Table 8
Change in column member forces due to the effect of soil–structure interaction for Tank 1 (aspect ratio = 0.31)

Alternate configuration	Type of clay	Axial force (kN)		Bending moment (kN m)		Shear force (kN)	
			% change due to *ssi*		% change due to *ssi*		% change due to *ssi*
At full condition							
With radial beams	Fixed base	491.44	—	175.18	—	127.89	—
	Very soft	569.08	15.79	201.78	15.18	146.49	14.54
	Medium	484.80	−1.35	168.34	−3.90	122.36	−4.32
	Very stiff	487.79	−0.74	171.39	−2.16	125.91	−1.54
With radial beams and central column	Fixed base	494.14	—	153.54	—	111.73	—
	Very soft	569.62	15.27	176.33	14.84	127.70	14.47
	Medium	486.37	−1.57	146.37	−4.66	103.28	−7.56
	Very stiff	490.67	−0.70	149.93	−2.35	109.39	−2.09
With two concentric rows of columns	Fixed base	437.19	—	83.29	—	59.83	—
	Very soft	509.45	16.52	96.58	15.95	69.37	15.94
	Medium	445.62	1.92	87.21	4.70	63.86	6.73
	Very stiff	438.38	0.27	84.16	1.04	61.19	2.27
With diagonal braces	Fixed base	468.68	—	122.88	—	87.97	—
	Very soft	544.65	16.20	142.51	15.97	102.83	16.89
	Medium	457.91	−2.29	116.38	−5.28	84.18	−4.30
	Very stiff	463.18	−1.17	119.85	−2.45	86.03	−2.20
At empty condition							
With radial beams	Fixed base	419.47	—	120.42	—	87.44	—
	Very soft	525.53	25.26	150.47	24.95	109.31	25.01
	Medium	439.59	4.79	125.73	4.40	91.35	4.47
	Very stiff	427.64	1.94	122.36	1.61	88.89	1.65
With radial beams and central column	Fixed base	420.79	—	105.60	—	76.38	—
	Very soft	530.25	26.01	132.67	25.63	96.0	25.68
	Medium	441.61	4.94	110.38	4.52	79.87	4.56
	Very stiff	429.10	1.97	107.28	1.68	77.63	1.63
With two concentric rows of columns	Fixed base	363.36	—	57.41	—	40.87	—
	Very soft	462.29	27.22	73.49	28.0	52.29	27.94
	Medium	382.03	5.13	60.66	5.66	43.16	5.60
	Very stiff	369.53	1.69	58.68	2.12	41.76	2.17
With diagonal braces	Fixed base	398.43	—	84.55	—	60.09	—
	Very soft	505.78	26.94	107.04	26.59	76.12	26.67
	Medium	419.35	5.25	88.64	4.83	63.03	4.89
	Very stiff	406.82	2.10	86.01	1.72	61.16	1.78

tank-empty conditions. Table 9 presents the same for Tank 2. The tables clearly indicate that the effect of soil–structure interaction on column forces is similar to that obtained for seismic base shear.

In Table 10, the seismic base shear of Tank 1 with an aspect ratio of 0.86 and that of Tank 2 with an aspect ratio of 0.61 at full condition are presented both at fixed base and flexible base

Table 9
Change in column member forces due to the effect of soil–structure interaction for Tank 2 (aspect ratio = 0.33)

Alternate configuration	Type of clay	Axial force (kN)		Bending moment (kNm)		Shear force (kN)	
			% change due to *ssi*		% change due to *ssi*		% change due to *ssi*
At full condition							
With radial beams	Fixed base	494.19	—	284.79	—	212.57	—
	Very soft	450.84	−8.77	261.58	−8.15	195.61	−7.98
	Medium	467.02	−5.49	270.32	−5.08	202.26	−4.85
	Very stiff	487.19	−1.41	281.91	−1.01	210.55	−0.95
With radial beams and central column	Fixed base	496.78	—	259.85	—	193.77	—
	Very soft	458.23	−7.75	240.83	−7.32	179.80	−7.21
	Medium	472.33	−4.92	247.95	−4.58	185.34	−4.35
	Very stiff	489.27	−1.50	256.91	−1.13	191.77	−1.03
With two concentric rows of columns	Fixed base	459.52	—	125.05	—	92.66	—
	Very soft	489.38	6.49	132.83	6.22	98.25	6.03
	Medium	468.44	1.94	126.75	1.36	93.71	1.13
	Very stiff	462.81	0.71	125.70	0.52	93.10	0.48
With diagonal braces	Fixed base	471.97	—	192.39	—	143.17	—
	Very soft	432.94	−8.26	177.29	−7.85	132.32	−7.58
	Medium	459.81	−2.57	188.12	−2.22	140.12	−2.08
	Very stiff	464.13	−1.66	189.97	−1.26	141.57	−1.12
At empty condition							
With radial beams	Fixed base	340.25	—	157.60	—	117.45	—
	Very soft	431.08	26.69	197.53	25.33	147.37	25.54
	Medium	363.45	6.81	166.62	5.72	124.30	5.83
	Very stiff	350.20	2.92	161.06	2.19	120.16	2.30
With radial beams and central column	Fixed base	341.26	—	143.64	—	106.92	—
	Very soft	435.01	27.47	180.96	25.98	134.87	26.14
	Medium	365.38	7.06	152.02	5.83	113.30	5.96
	Very stiff	351.67	3.05	146.79	2.19	109.40	2.31
With two concentric rows of columns	Fixed base	303.44	—	68.76	—	50.81	—
	Very soft	373.90	23.22	87.31	26.97	63.33	24.64
	Medium	314.69	3.70	73.66	7.12	53.47	5.23
	Very stiff	301.59	−0.60	70.73	2.86	51.36	1.08
With diagonal braces	Fixed base	322.71	—	106.11	—	78.78	—
	Very soft	412.68	27.87	138.26	30.29	101.43	28.75
	Medium	346.43	7.35	115.93	9.25	85.10	8.02
	Very stiff	332.91	3.16	111.67	5.39	81.99	4.07

condition. The results of these cases help to understand the effect of larger aspect ratio for the tank container implying a large impulsive mass. However, the effect of soil-flexibility on seismic base shear shows a less pronounced effect with respect to the tanks having lesser aspect ratios. The tanks having greater aspect ratio have a smaller container radius. This will result in a larger

Table 10
Change in seismic base shear due to the effect of soil–structure interaction for Tank 1 (aspect ratio = 0.86) and Tank 2 (aspect ratio = 0.61) at tank full condition without and with effect of soil–structure interaction

Alternate configuration	Type of clay	Seismic base shear (kN)					
		Tank 1			Tank 2		
		Without *ssi*	With *ssi*	% change	Without *ssi*	With *ssi*	% change
With radial beams	Very soft	1645.20	1842.62	11.99	6434.29	5496.99	−14.56
	Medium		1732.16	5.28		5680.83	−11.71
	Very stiff		1661.69	1.0		5991.61	−6.88
With radial beams and central column	Very soft	1645.02	1867.09	13.49	6447.35	5712.35	−11.40
	Medium		1736.75	5.57		5821.08	−9.71
	Very stiff		1662.20	1.04		6074.04	−5.79
With two concentric rows of columns	Very soft	1643.38	1856.62	12.97	6521.42	6104.05	−6.39
	Medium		1755.74	6.83		6338.82	−2.80
	Very stiff		1664.62	1.29		6436.64	−1.30
With diagonal braces	Very soft	1644.71	1863.28	13.28	6449.38	5610.34	−13.0
	Medium		1743.48	6.0		5692.28	−11.73
	Very stiff		1663.0	1.11		5997.62	−7.0

impulsive mass of water which is perhaps responsible for a less pronounced effect of soil–structure interaction.

If the impulsive lateral period is short enough to be in the sharply rising acceleration sensitive zone of design spectrum, the increase in lateral period due to consideration of soil-flexibility may cause an increase in spectral ordinate. Moreover, increase in impulsive lateral period, takes it closer to the convective period. This may result in an increase in cross-modal terms arising from the increased coupling between impulsive and convective modes. The combined effect of these two factors may perhaps be the reason behind the increase in base shear.

The seismic base shear induces axial compression in half of the staging columns and tension in the remaining ones. The value of maximum axial compression and tension due to seismic base shear are same and occur in two columns located at diametrically opposite sides. It is observed that in tank-full condition, the axial compressive force due to weight of container and water is sufficient to counterbalance the maximum axial tensile force. Hence, in this case all the columns remain under compression. On the other hand, under tank-empty condition, there remains a possibility of occurring axial tension due to considerable reduction in axial compression resulting from lesser self-weight. Thus, increase in axial tension in column, due to increase in base shear resulting from soil-flexibility, may lead to an overall axial tension over and above the reduced compressive force due to lesser self-weight. It can be observed from the investigation that in cases of Tank 1 with radial beams and with diagonal braces and in case of Tank 2 with diagonal braces, though there is no possibility of occurring axial tension in columns from the analysis based on fixed base condition, the axial tensile force may occur in columns due to increase in seismic base shear resulting from soil–structure interaction. Thus, ignoring soil–structure interaction through a fixed base assumption of elevated water tanks may lead to an unsafe seismic design of elevated water tanks particularly at empty condition.

The elevated water tanks are considered to be torsionally vulnerable if they have impulsive torsional-to-lateral period ratio, τ, in a critical range of 0.7–1.25 [1,6]. Hence, as per suggestion of the literature [5] it is of great importance to check whether τ lies within 0.7–1.25 for assessing torsional vulnerability and to change the staging configuration, accordingly, to bring τ outside the critical range. So, correct assessment of this ratio, τ, is very important. Ignoring soil–structure interaction may lead to a wrong assessment of seismic torsional vulnerability of elevated water tank. Table 11 presents torsional-to-lateral period ratio for two example elevated water tanks at tank-full and tank-empty conditions, respectively, considering fixed base condition as well as flexible base condition. For the first one with all the four alternate configurations, torsional-to-lateral period ratio, at fixed base condition, does not lie in the critical range of 0.7–1.25 and hence the tank does not seem to be torsionally vulnerable at tank-full condition. However, in reality, the elevated tank actually may have its torsional-to-lateral period ratio within a critical range of 0.7–1.25 due to the consideration of soil-flexibility and thus, may undergo a seismic torsional failure even at tank-full condition. On the other hand, for the other example tank having alternate staging configuration with radial beams and central column and that with two concentric rows of columns, the tanks appear to be less torsionally vulnerable at tank-empty condition as τ is found to lie outside the critical range due to the consideration of a fixed base condition. But, incorporation of soil-flexibility shows that actually τ will be within the critical range for most of the soil conditions. Hence, neglecting the effect of soil–structure interaction may lead to erroneous inference regarding torsional vulnerability of the structure.

9. Summary and conclusions

The present paper attempts to study the effect of soil–structure interaction on two important dynamic characteristics of elevated tanks supported by frame staging with a few alternate configurations. These configurations are not only required to be adopted to keep the value of τ outside the critical range of 0.7–1.25 but also to increase the redundancy of the staging structure resulting in better inelastic range seismic performance. Analytical formulations are validated and employed in the present study so that influential parameters can be well identified and can be varied within their feasible range of variations. Following conclusions can be arrived from the study:

1. The effect of soil–structure interaction considerably increases the impulsive lateral period and decreases the impulsive torsional-to-lateral period ratio.
2. The effect of soil-flexibility is found to be stronger for elevated tanks supported by alternate frame staging configurations with panels of small heights, and larger number of columns, large column diameter and stiffer circumferential beams compared to the columns.
3. The analytical formulations developed in the present study are validated against the results of finite element analysis. Hence, these formulations as well as variation curves drawn from them can be used in design offices to incorporate the effect of soil–structure interaction in seismic design of elevated tanks, with these types of alternate staging configurations.

Table 11
Comparison of torsional-to-lateral natural period ratio, τ, due to use of alternate staging configuration for Tanks 1 and 2 resting on circular raft foundation

Alternate configuration	Type of clay	Torsional-to-lateral natural period ratio, τ					
		Tank full condition			Tank empty condition		
		Without *ssi*	With *ssi*	% change	Without *ssi*	With *ssi*	% change
Tank 1							−27.44
With radial beams	Very soft	1.433	1.041	−27.36	1.793	1.301	
	Medium		1.098	−23.38		1.375	−23.31
	Very stiff		1.179	−17.73		1.475	−17.74
With radial beams and central column	Very soft	1.536	1.074	−30.08	1.921	1.346	−29.93
	Medium		1.137	−25.98		1.422	−25.98
	Very stiff		1.229	−19.99		1.537	−19.99
With two concentric rows of columns	Very soft	1.890	1.090	−42.33	2.374	1.364	−42.54
	Medium		1.173	−37.94		1.464	−38.33
	Very stiff		1.301	−31.16		1.628	−31.42
With diagonal braces	Very soft	1.329	0.934	−29.72	1.660	1.169	−29.58
	Medium		0.991	−25.43		1.242	−25.18
	Very stiff		1.073	−19.26		1.339	−19.34
Tank 2							
With radial beams	Very soft	0.938	0.715	−23.77	1.215	0.925	−23.87
	Medium		0.806	−14.07		1.041	−14.32
	Very stiff		0.864	−7.89		1.117	−8.07
With radial beams and central column	Very soft	0.976	0.729	−25.31	1.261	0.944	−25.14
	Medium		0.826	−15.37		1.067	−15.38
	Very stiff		0.891	−8.71		1.154	−8.48
With two concentric rows of columns	Very soft	1.240	0.758	−38.87	1.602	0.979	−38.89
	Medium		0.903	−27.18		1.167	−27.15
	Very stiff		1.024	−17.42		1.329	−17.04
With diagonal braces	Very soft	0.868	0.649	−25.23	1.124	0.839	−25.36
	Medium		0.736	−15.21		0.952	−15.30
	Very stiff		0.793	−8.64		1.026	−8.72

In Tables 7 and 8, columns titled as 'without *ssi*' represents the results at fixed support condition whereas that titled as 'with *ssi*' represents the results considering the effect of soil–structure interaction.

4. The study shows that analysis with fixed base assumption may lead to underestimation or overestimation of seismic base shear of elevated tanks with any alternate staging configuration at both tank-full and tank-empty conditions. The soil-flexibility may endanger the elevated tank structures by developing tension in some of the staging columns at tank-empty condition which may be overlooked if designed on the basis of a fixed base assumption. Ignoring soil–structure interaction may also lead to wrong assessment of torsional vulnerability of such elevated water tanks.

5. The staging with two concentric rows of columns or that with diagonal braces are used for their larger structural redundancy and also for the fact that their use may help to have torsional-to-lateral period ratio outside the critical range. However, considerable effect of soil–structure interaction on dynamic characteristics of both of them due to their stiffer structural configurations should be accounted for seismic design.

In an overall sense, the present study highlights the importance of soil–structure interaction and its impact on seismic design of elevated tanks with alternate staging configurations. The analytical formulations as well as the variation curves presented in the study may prove useful to the design engineers to incorporate the effect of soil–structure interaction on dynamic characteristics of elevated tanks supported by alternate frame staging configurations, very conveniently.

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