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TORSIONAL FAILURE OF ELEVATED WATER TANKS : THE PROBLEM AND SOME SOLUTIONS

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ABSTRACT

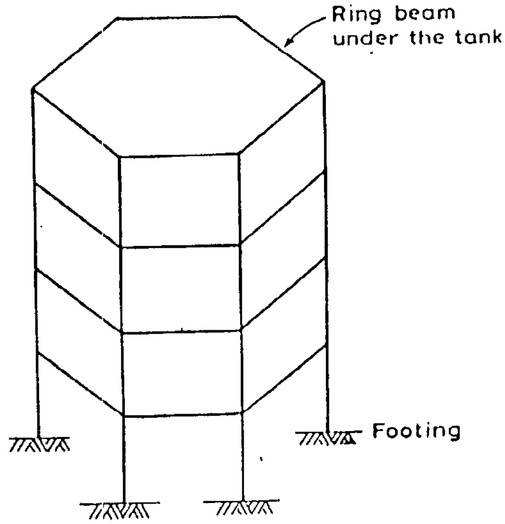
Elevated water tanks have failed in past earthquakes due to torsional vibration. Large torsional response generally unexpected in this type of structures due to overall axisymmetry of the system. However, the presen of small eccentricity (e) in such systems may lead to either amplified rotation or large element displacement their torsional-to-lateral natural period ratio (τ) lies within a critical range ($0.7<\tau<1.25$). It is seen that mo usually-constructed reinforced concrete elevated tanks supported on moment resisting frame type stagings m have τ in the critical range. Four alternate tank staging configurations are discussed which may be used to ensu that τ lies outside the critical range.

KEYWORDS

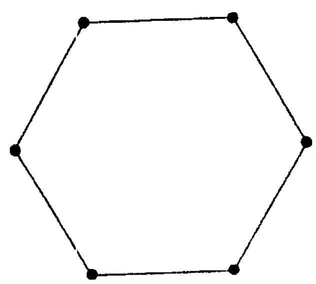
Earthquake Analysis; Elevated Tanks; Inelastic; Natural Period Ratio; Seismic Response; Staging Configuration; Strength Deterioration; Torsion; Torsional Coupling.

INTRODUCTION

Elevated water tanks have failed during past earthquakes (*e.g.*, Steinbrugge, 1970) owing to large torsional response. More recently, one reinforced concrete elevated water tank collapsed vertically downwards, burying the six supporting columns directly underneath the bottom slab of its container during the 1993 Killari, India, earthquake (Jain *et al,* 1994). This vertical collapse and the evidence of a circumferential displacement of about 0.5 metre suggest that torsional vibrations may have been the primary cause of its failure. Elevated water tanks, with their broadly axisymmetric geometry and mass distribution, do not appear to be prone to torsion. However, asymmetric placement of ladders and water pipelines, sloshing of the water mass during shaking, and non-uniformity in construction are some possible causes for developing small initial eccentricity in elevated water tanks. This paper summarizes a recent study on torsional response of R.C. elevated water tanks supported on axisymmetric moment-resisting frame type staging (Dutta, 1995). It describes the possible reasons for magnified torsional response in such tanks (Fig.1a). Four alternate staging configurations (Figs.1b,1c,1d &1e) are suggested which may be used to avoid the problem.

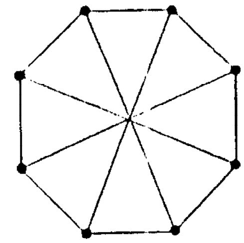


Isometric view

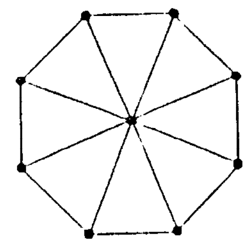


Plan

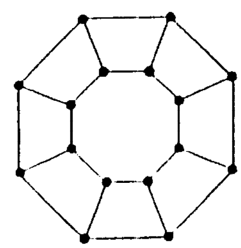
(a) Usual configuration



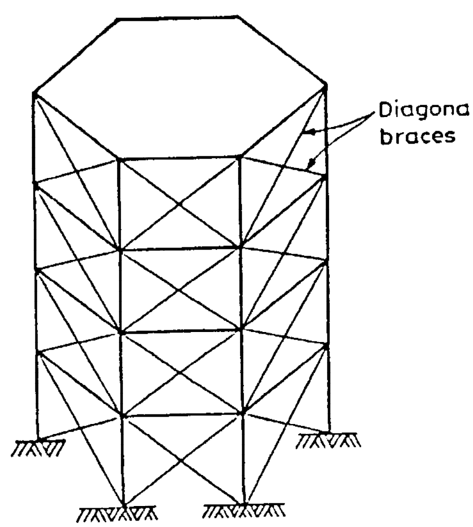
(b) Staging with radial beams



(c) Staging with radial beams and a central column



(d) Staging with two-concentric rows of columns, circumferential beams and radial beams



(e) Staging with diagonal braces.

ELASTIC RESPONSE

Elevated water tanks on frame stagings are idealized as small-eccentricity systems with two and four lateral load resisting elements (Fig.2). The elevated water tanks have impulsive and sloshing modes of vibration under earthquake ground motion. The natural periods of the sloshing modes of vibration are usually much larger than those of the impulsive modes and the natural periods contained in the earthquake ground motions. Hence, only the first impulsive mode in translation and the first impulsive mode in torsion are considered here. The tank system is idealized as a lateral-torsionally coupled two degrees of freedom system (Fig.2). In the four-element systems, only the two elements in the direction of lateral force carry the entire lateral force while all the four elements participate in resisting torsion. In the two-element system, both the elements being oriented in the direction of lateral force participate in resisting lateral force as well as torsion. From the view-point of torsional-to-lateral stiffness and strength ratios, the four-element system represents the dynamics of stagings with large number of panels and large number of columns, while a two-element system represents a four column staging with small number of panels.

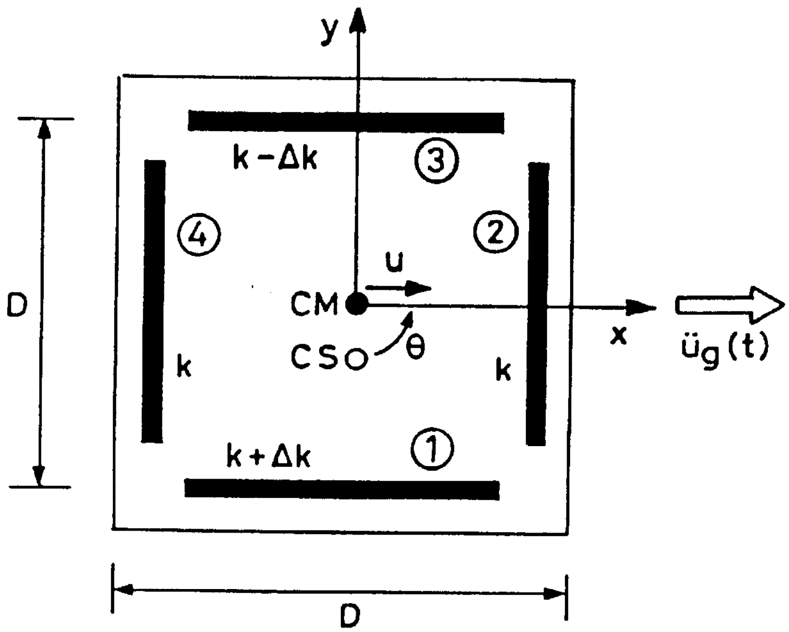
The linear dynamic responses of these idealized systems were studied under harmonic ground motion, synthetic ground motion consistent with a typical design spectrum, and ground motions with flat and hyperbolic response spectra (Dutta, 1995).

It is observed that when torsional-to-lateral natural period ratio τ is very close to 1, the tanks exhibit maximum rotation and minimum element displacement. However, the range $0.7<\tau<1.25$ contains two maxima in maximum element displacement one each on either side of the minimum value at $\tau\approx1$. Hence, this range is identified as critical for either maximum rotation or for excessive element displacement. A sample result obtained under ground motion with idealized flat response spectrum is shown in Fig.3. The figure presents the maximum element displacements of flexible and stiff elements of four-element and two-element small-eccentricity systems (e/D=0.05); the maximum element displacements have been normalized with respect to the displacement of the corresponding symmetric system. Further, Fig.3 shows that two-element systems experience larger maximum element displacement than their four-element counterparts. This implies that RC elevated water tanks with less number of panels and columns are more susceptible to the effect of torsional coupling.

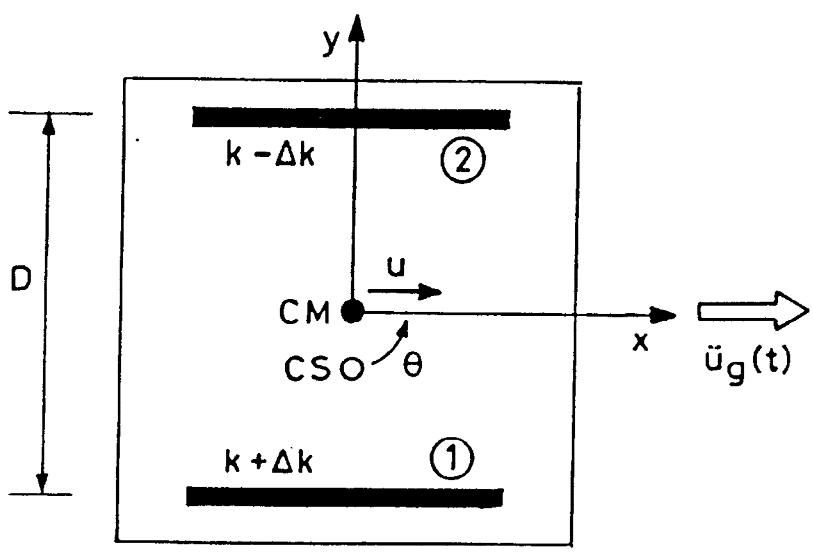
INELASTIC RESPONSE

Inelastic response of the idealized systems was studied under a synthetic ground motion time history. RC frame members undergo strength deterioration under cyclic loading. If unsymmetric yielding takes place in a strength-deteriorating system due to small eccentricity, it causes further relative deterioration in strength in the yielded elements resulting in larger strength eccentricity, and hence may result in a progressively increasing torsional response. A simple analytical model was developed for broadly capturing the elastic-perfectly plastic strength-deteriorating hysteresis behaviour of individual lateral force resisting elements. The progressive torsion-induced damage in RC stagings under cyclic loading was studied using this model.

Increased torsional response due to strength deterioration is found to be more severe in the stiffness-symmetric strength-eccentric systems than in the corresponding stiffness-eccentric strength-symmetric systems. The variation of normalized maximum element displacement with τ for different values of strength deterioration parameter (δ) with T_X=0.5 sec and small eccentricity e/D=0.5, is shown in Fig.4. Two sets of graphs are provided corresponding to ductility reduction factor $R_\mu = 1$ and $R_\mu = 2$ used in designing the yield strength of the system. Strength deterioration parameter (δ) is the fractional change in yield strength of the reinforced concrete system for each occurrence of yielding. The maximum element displacement has been normalized with respect to the maximum element displacement of the corresponding symmetric system; hence, the ordinate values in Fig. 4 give the factor by which the member ductility demand increases on account of torsion. The figure clearly shows that there could be large inelastic torsion response if the rate of strength deterioration is significant. Also, increase in member ductility demand on account of torsion is larger



(a) Four-element system ($K_x = 2k$, $K_\theta = kD^2$)



(b) Two-element system ($K_x = 2k$, $K_\theta = kD^2/2$)

Fig. 2. Idealized systems considered to model lateral-torsional coupling in elevated water tanks

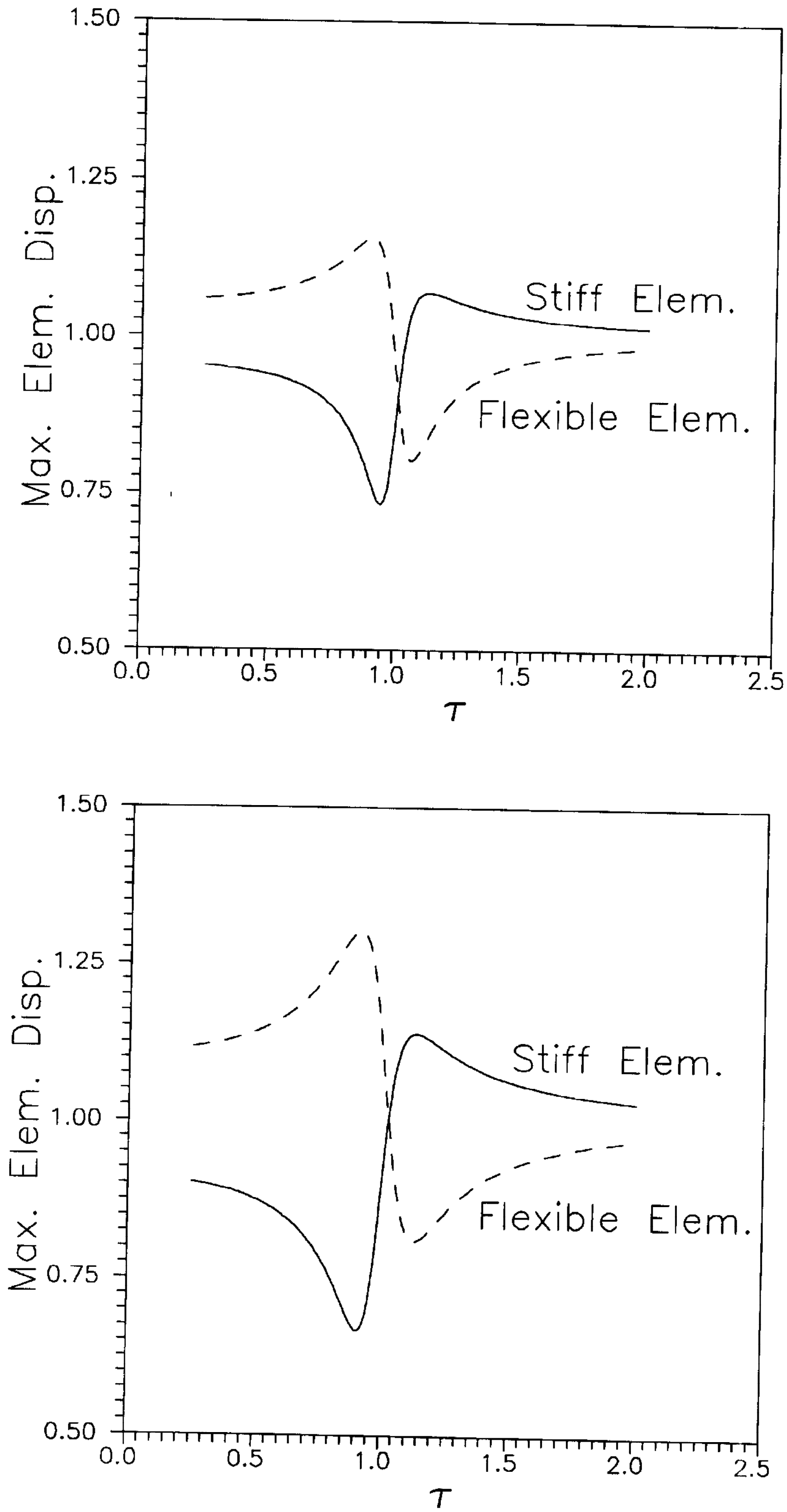


Fig. 3. **Maximum normalized element displacement under ground motions with flat acceleration spectrum (elastic analysis).**

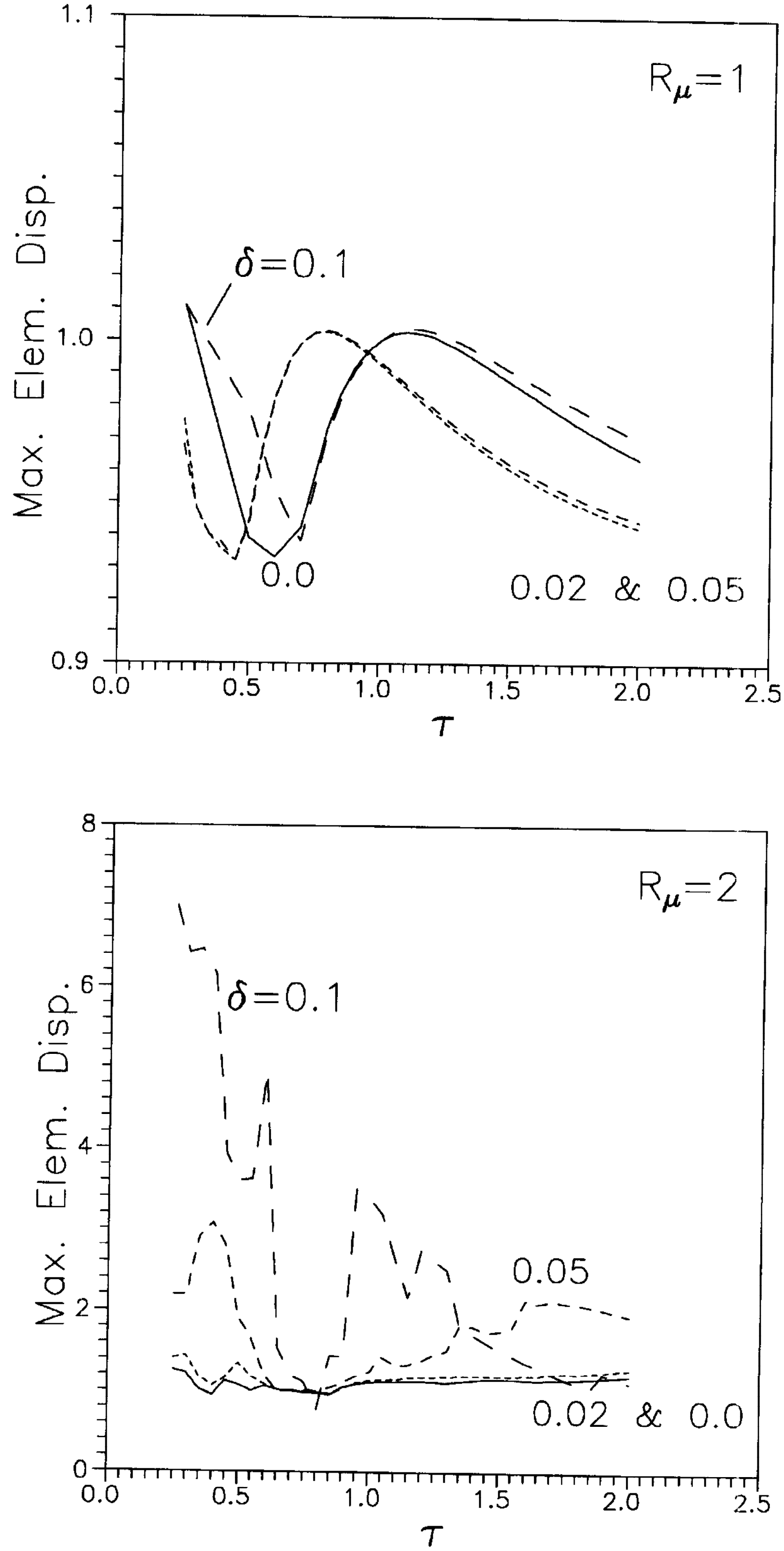


Fig. 4. **Maximum normalized element displacement of strength-eccentric stiffness-symmetric two-element system: inelastic response ($T_x = 1$ sec, $e_{strength} / D = 0.05$)**

for systems designed to respond inelastically under design earthquake condition (*i.e.*, $R_\mu = 2$) than that for systems designed to remain elastic (*i.e.*, $R_\mu = 1$). In case of $R_\mu = 2$, the member ductility demand can go up by a factor of 2 or even more due to torsion.

Idealized two-element systems representing stagings with small number of panels and columns, are found to be more vulnerable to torsional response amplification with strength deteriorating property than the idealized four-element systems representing stagings with many panels and columns. The effect of bi-directional ground motion is found to be higher than that of a single directional one on the four-element system.

STUDY OF TORSIONAL-TO-LATERAL NATURAL PERIOD RATIO (τ)

That small-eccentricity systems exhibit considerable rotational response under translational ground motion, if the uncoupled torsional and lateral time periods are close to each other, is well established in the context of building systems (Kan and Chopra, 1977; Tso and Dempsey, 1980). Elastic analyses show that τ is a primary parameter which regulates the magnification of rotation of centre of mass as well as the element displacement in the small-eccentricity systems.

With reference to elevated water tanks, an approximate analytical method for calculating the lateral stiffness and member design forces of frame-type stagings is outlined in the literature (Sameer and Jain, 1992; Sameer and Jain, 1994). Approximate expressions for deriving torsional stiffness and member forces under torsional moment have been derived (Dutta, 1995). Approximate closed-form expressions of torsional and lateral time periods, and their ratio were derived for elevated water tanks supported on frame stagings of the types shown in Fig.1.

For tank stagings of basic configuration (Fig.1a) with usual range of the parameters, namely the relative flexural stiffness of columns with respect to that of circumferential beams (K_r), number of panels (N_p), and number of columns (N_c), most of the elevated water tanks were found to have τ in the critical range $0.7<\tau<1.25$ under tank empty, tank full or intermediate water-depth conditions. Thus, the problem of amplified torsional response exists in many of these tanks.

The alternate staging configurations with radial beams (Fig.1b), with radial beams and a central column (Fig.1c), and with two circular rows of columns (Fig.1d), increase τ. The radial beams and central column do not contribute to torsional stiffness while they increase lateral stiffness by increasing framing action. In the configuration of Fig.1d, the inner circular row of columns contributes less to torsional stiffness because of smaller radius while it adds substantially to lateral stiffness. Configuration of Fig. 1e can be used to reduce τ since the diagonal braces induce truss action, which creates relatively smaller increase in lateral stiffness than in torsional stiffness. These alternate configurations may be considered in order to keep τ outside the critical range, and therefore the problem of large torsional response can be avoided.

CONCLUSIONS

The commonly constructed RC elevated water tanks with basic staging configuration (Fig.1a) may be highly susceptible to amplified torsional response during earthquakes since they often have τ within the critical range $0.7<\tau<1.25$. The problem of torsion-induced large displacements in inelastic range is quite real due to strength-deteriorating property of concrete members. The elevated water tanks should, therefore, be designed such that τ lies outside the identified critical range. Four alternate staging configurations are indicated which can be used to achieve this. In general, elevated tanks supported on more number of columns and with large number of panels undergo less torsional response than those on fewer columns and panels. Stagings designed to respond inelastically under design seismic conditions (*i.e.*, large ductility reduction factor used in design) may have significant torsional response amplification due to strength deterioration of concrete members.

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