1. INTRODUCTION

1.1 Introduction

Water tanks are lifeline items in the aftermath of earthquakes. The current practice of designing elevated water tanks (Figure 1.1) is resulting in tanks that are extremely vulnerable under lateral forces due to earthquake shaking, as observed in the recent earthquakes in India. In addition, seismic design is not being performed in many seismic areas in India, and supervision during construction is inadequate. Shaft type stagings have poor ductility of the thin sections and also lack redundancy of alternate load paths. This makes it necessary to assess safety of existing elevated water tanks of that are largely gravity designed and poorly constructed. Based on the above common deficiencies, a procedure is described below for *Rapid Assessment* of *earthquake safety* of existing Elevated Water Tanks with Reinforced Concrete Shaft Stagings in India, considering primarily the shear capacity of RC shaft staging, even though flexure capacities of the shaft also is a critical parameter governing earthquake safety of such tank.

1.2 Assumptions

The following assumptions are made in the *Rapid Evaluation of Seismic Safety of Elevated Water Tanks with Shaft Staging*:

(1) Fundamental natural period of the tank system is based on single degree of freedom model of the tank structure ignoring the convective vibration modes of water.
(2) Shaft is a cantilever with the concentrated mass of the tank container at its tip.
(3) Mass and stiffness of the shaft staging are uniformly distributed along its height.

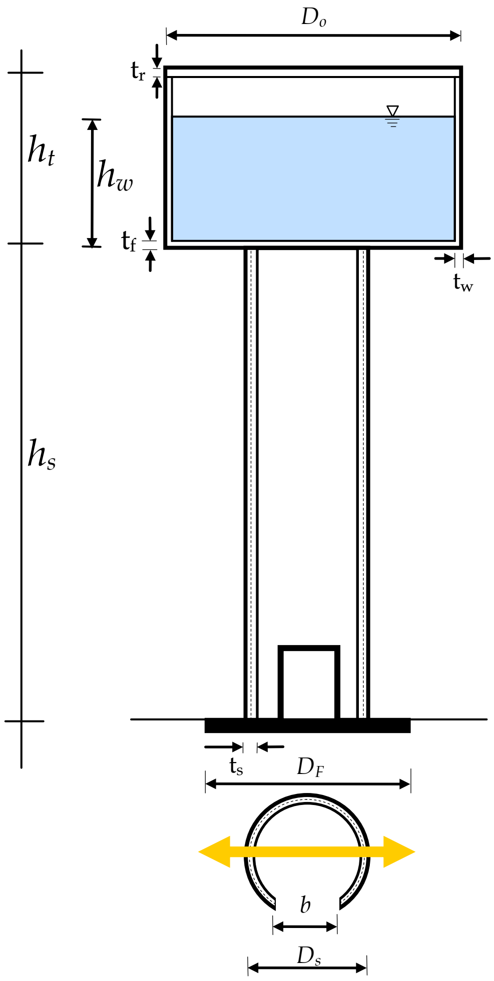

Figure 1.1: Elevated Water Tanks with Shaft Staging

1.3 Shear Demand on Shaft Staging

The shear demand on beams and columns is estimated by

(1) Obtaining the design lateral earthquake force on the tank as per the expression given in IS:1893(Part 1)-2002, and

(2) Obtaining the design shear force on the shaft staging through approximate structural analysis method.

1.3.1 Design Horizontal Seismic Force V_b

The design seismic base shear V_B shall be determined by

$$V_b = A_h W_s , \tag{1}$$

V_b is estimated for both tank empty and tank full conditions, and the higher used. In Eq.(1), design horizontal seismic coefficient, A_h shall be obtained by:

$$A_h = \frac{Z_{SS} I}{R}\left(\frac{S_a}{g}\right), \tag{2}$$

where

Z_{SS} = Site-specific horizontal acceleration expected at the location of the Tank (expressed as a fraction of Acceleration due to gravity)

I = Importance factor = 1.5 for water storage tanks (because of post-earthquake importance);

R = Response reduction factor
= 1.8 for frames without ductile detailing
= 2.5 for frames with ductile detailing; and

S_a/g= Average response acceleration coefficient depending on soil type

$$= \begin{cases} 2.5 & 0 \le T \le 0.4 \\ 1.00/T & 0.4 \le T \le 4.0 \end{cases} \quad \text{for Soil Type I } \mathbf{(N>30)}$$

$$= \begin{cases} 2.5 & 0 \le T \le 0.55 \\ 1.36/T & 0.55 \le T \le 4.0 \end{cases} \quad \text{for Soil Type II } \mathbf{(15<N<30)}$$

$$= \begin{cases} 2.5 & 0 \le T \le 0.67 \\ 1.67/T & 0.67 \le T \le 4.0 \end{cases} \quad \text{for Soil Type III } \mathbf{(N<10)}$$

in which N is the Standard Penetration Test value.

1.3.2 Natural Period T of Tank

In Eq.(2), the natural period T of the tank shall be obtained by:

$$T = C_T \sqrt{\frac{W_t h_s}{E_s A_s g}} , \tag{3}$$

where W_t is the equivalent seismic weight of the tank system depending on empty or filled condition, h_s staging height, A_s the cross sectional area of the staging. C_T, which depends on slenderness ratio of the staging, is given by $k = \left(\frac{h_s}{r_e}\right)$, where r_e is radius of gyration of the staging (Table 6 of IS: 1893 (1984)).

1.3.3 Seismic Weight W_t

Research showed that when weight W_{tank} of the tank is much greater than that of the staging $W_{staging,}$ the equivalent mass W_t may be taken as:

$$W_t = W_{tank} + \frac{W_{staging}}{3} . \tag{4}$$

In Eq.(4), only 1/3 of the staging mass is found to be effective at the centroid of the tank from energy considerations; 2/3 of the staging mass is found to be effective at the bottom of the tank (at the ground level) and does not contribute to the vibration of the system.

1.3.4 Shear Demand on Shaft Staging

The circular shear wall is idealized as two parallel shear wall of length $l_e = 0.78D_s$, where D_s is the diameter of the circular wall (Figure 1.2). This idealization is based on the fact that the in-plane shear is assumed to be resisted by this two parallel shear walls. The design shear force per unit of effective shear wall length is equal to the maximum in-plane shear in a cylinder without opening, $2V_b/\pi D_s$. The total shear V_b is distributed to the two shear walls in proportion to their areas. At sections without openings are symmetrical openings, $0.5V_b$ is assigned to each shear wall. At sections with unsymmetrical openings, a torsional moment changes the shear force distribution by $V_T = \pm V_b e/D_s$ .Hence the total shear demand on the shaft staging is given by

$$V_d = 0.5V_b \pm V_T , \tag{5}$$

where

$\psi = \dfrac{b}{l_e}$ = Ratio of the width of openings to length of equivalent shear wall ($0.78D_s$); and

$e = 0.5D_s\left(\dfrac{\psi}{2-\psi}\right)$ = The eccentricity due to the opening

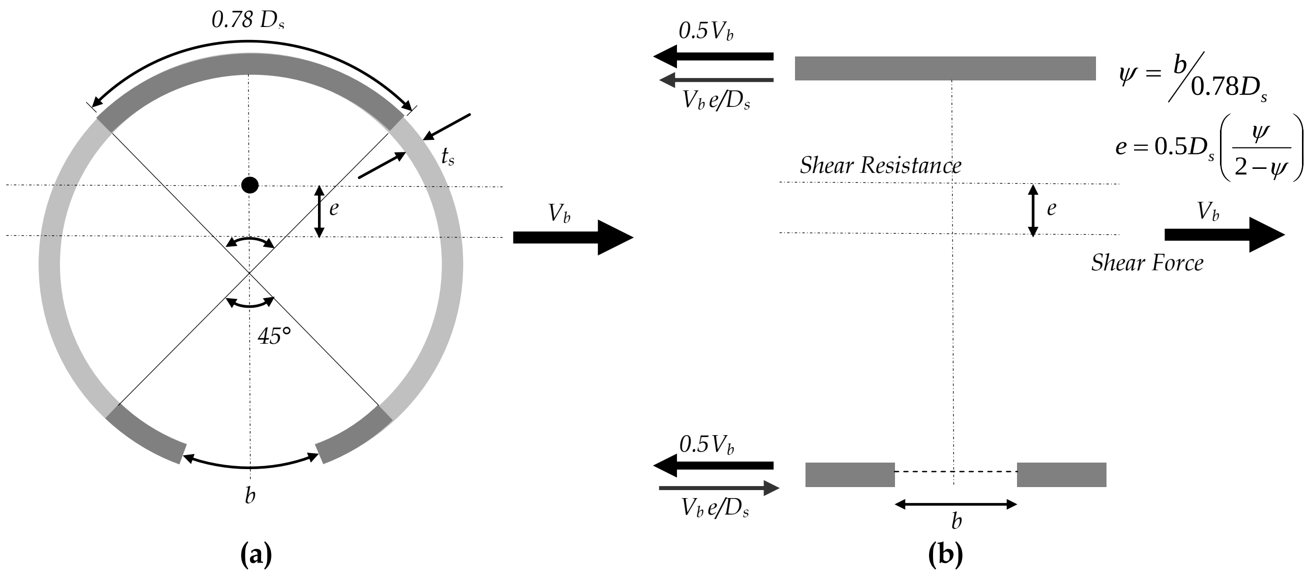

Figure 1.2: Elevated Water Tank with Shaft Staging: (a) Circular section resisting lateral shear, and (b) Equivalent shear wall model for computing lateral shear strength.

1.4 Shear Capacity and Shear Checks of Shaft

The Shear Capacity of the Shaft Staging is calculated as sum of the shears resisted by concrete V_c and the transverse steel reinforcement V_s, as

$$V_{u,shaft} = V_{uc} + V_{us} \tag{6}$$

For a percentage of longitudinal reinforcement ρ in shaft wall and the grade of concrete from Table 19 of IS:456-2000, the *design shear strength of concrete* τ_c is obtained. The check is performed at the weakest section along the height of the shaft, which is the one with the largest opening.

Shear resistance offered by concrete is calculated as

$$V_{uc} = \tau_c A_c , \tag{7}$$

where $A_c = 0.8(l_e - b)t_s$, is the area of cross section through the shaft staging with opening. And, shear resistance offered by transverse steel is calculated as

$$V_{us} = 0.87 f_y A_{st} \frac{0.8 l_e - b}{s_v}, \tag{8}$$

where
f_y = Yield Stress of Steel reinforcement
A_{st} = Area of cross section of transverse reinforcement
l_e = Equivalent Shear Wall length
b = With of Opening
s_v = Spacing of transverse reinforcement

If the *Shear Capacity* $V_{u,shaft}$ of the shaft staging is greater than the *Shear Demand* $V_{d,shaft}$ on the shaft staging, *i.e.,*

$$V_{u,shaft} > V_{d,shaft}, \tag{9}$$

then the staging is considered to be safe.

1.5 Checks for Stability of Shaft Staging

For the water tank to be safe against overturning, the *Overturning Moment* M_{OT} generated due to the lateral earthquake shaking should be smaller than the Restoring Moment M_R due the self weight of the tank system (*i.e.,* tank, staging and foundation). But, Restoring Moment is reduced when the effects due to vertical motion of earthquakes are considered. The design vertical acceleration spectrum is taken as two-thirds of the design horizontal acceleration spectrum as specified in Clause 6.4.2. of IS 1893 (Part 1): 2002. *i.e.,* $V_v = \left(\frac{2}{3}\right) V_b$. To ensure safety, a factor of safety of 1.5 is considered to be a minimum value against overturning, *i.e.,*

$$M_R \left(1 - \frac{2}{3} A_h\right) \geq 1.5 M_{OT} \tag{10}$$

or

$$\left(W_{\text{tank}} + W_{\text{staging}} + W_{\text{foundation}}\right)\left(1 - \frac{2}{3} A_h\right)\frac{D_F}{2} \geq V_B \left(h_s + \frac{h_t}{2}\right) \tag{11}$$

where
V_b = Base Shear;
h_s, h_t = height of staging and tank, respectively;
W_{tank} , $W_{staging}$ = Weight of tank and staging respectively;
$W_{foundation}$ = Weight of foundation; and
D_F = Diameter of foundation.

References

IS:13920, (1993), *Code of Practice for Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces,* Bureau of Indian Standards, New Delhi

IS:1893, (1984), *Criteria for Earthquake Design of Structures,* Bureau of Indian Standards, New Delhi

IS:1893: Part 1, (2002), *Criteria for Earthquake Resistant Design of Structures – Part 1: General Provisions and Buildings,* Bureau of Indian Standards, New Delhi

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National Information Centre of Earthquake Engineering *NICEE,* (2007), *IITK-GSDMA Guidelines for Seismic Design of Liquid Storage Tanks*, Indian Institute of Technology Kanpur

Rai,D.C., (2002), "Review of Code Design Forces for Shaft Supports of Elevated Water Tanks," *Proceedings of 12th Symposium on Earthquake Engineering,* Indian Institute of Technology Roorkee

Rapid Assessment of Seismic Safety of
Elevated Water Tanks with SHAFT Staging

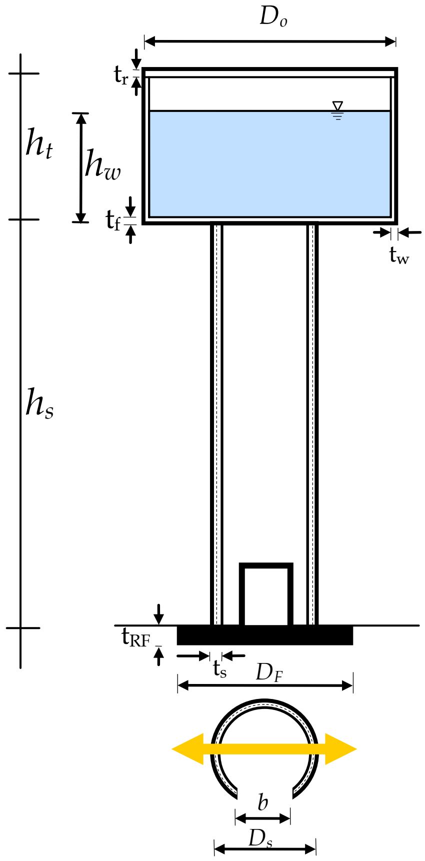
2. INPUTS

2.1 Basic Information

(1) Location :
(2) Type of Staging : Shaft
(3) Importance Factor I : 1.5
(4) Capacity : m^3
(5) Shape of Water Tank : Circular

Seismic Zone as per Indian Seismic Code:
Site-specific horizontal acceleration Z_{SS} :
Detailing Type: Ordinary / Special R = 1.8/2.5

2.2 Geometry



Inputs	*Units*
h_t	= m
D_o	= m
t_w	= m
t_r	= m
t_f	= m
h_w	= m
b	= m
h	= m
t_s	= m
h_s	= m
D_s	= m
D_F	= m
t_{RF}	= m
Vertical Reinforcement: *Transverse Reinforcement:*	

Figure 2.1: Elevated Water Tanks- Shaft Staging

2.3 Materials and Structural System

(1) Grade of Concrete f_{ck} = MPa Modulus of Elasticity, $E_c = 5000\sqrt{f_{ck}}$ = MPa

(2) Type of Soil **(Tick ONE)**

(i) *Rocky and Hard Soil*	**N>30**	:	Type I
(ii) *Medium Soil*	**30>N>10**	:	Type II
(iii) *Soft Soil*	**10<N**	:	Type III

3. BASIC SAFETY CHECKS

3.1 Section Properties

Derived Quantities	*Units*
$D_i = D_o - 2t_w$	= m
$W_{T\_empty} = \left[\left(\pi/4\right)\left(D_0^2 - D_i^2\right)h_t + \left(\pi/4\right)D_0^2\left(t_r + t_f\right)\right]\rho_{concrete}g$	= kN
$W_{water} = \left[\left(\pi/4\right)D_i^2 h_w\right]\rho_{water}g$	= kN
$W_{T\_full} = W_{T\_empty} + W_{water}$	= kN
$W_{staging} = \pi\left(D_s - t_s\right)t_s h_s \rho_{concrete}g$	= kN
$I_s = \pi R_s^3 t_s = \pi\left(\frac{D_s - t_s}{2}\right)^3 t_s$	= m⁴
$A_s = \pi\left(D_s - t_s\right)t_s$	= m²
$r_e = \sqrt{\frac{I_s}{A_s}}$	= m
$W_{s\_full} = W_{full} + \left(1/3\right)W_{staging}$	= kN
$W_{s\_empty} = W_{empty} + \left(1/3\right)W_{staging}$	= kN
$W_{foundation} = \left(\pi/4\right)D_F^2 t_{RF}\rho_{concrete}g$	= kN
Equivalent shear wall length $l_e = 0.78D_s =$ m $\psi = \frac{b}{l_e} =$	
Eccentricity e due to unsymmetrical opening $e = 0.5D_s\left(\frac{\psi}{2-\psi}\right) =$ m	

3.2 Natural Period of Tank

Tank Full $T_{full} = C_T \sqrt{\frac{W_{s\_full} h_s}{E_c A_s g}}$; Tank Empty $T_{empty} = C_T \sqrt{\frac{W_{s\_empty} h_s}{E_c A_s g}}$ where *staging slenderness ratio* $k = \left(\frac{h_s}{r_e}\right) =$; C_T =	T_{full} = s	T_{empty} = s

k	C_T
5	14.4
10	21.2
15	29.6
20	38.4
25	47.2
30	56.0
35	65.0
40	73.8
45	82.8
>50	1.8k

3.3 Design Horizontal Seismic Force

	Tank Full	Tank Empty
Spectral Acceleration (S_a/g)	$(S_a/g)_{full}$ =	$(S_a/g)_{empty}$ =
Horizontal seismic coefficient $A_h = \frac{Z_{SS} I}{R}\left(\frac{S_a}{g}\right)$	=	=
Base Shear Filled $V_B = A_h W_{s\_full}$; Empty $V_B = A_h W_{s\_empty}$	= kN	= kN
Governing Shear force V_B is greatest of Full and Empty condition	= kN	

Soil Type	*Spectral Acceleration (S_a/g)*
Type I	$\frac{S_a}{g} = \begin{cases} 2.5 & 0 \le T \le 0.4 \\ 1.00/T & 0.4 \le T \le 4.0 \end{cases}$
Type II	$\frac{S_a}{g} = \begin{cases} 2.5 & 0 \le T \le 0.55 \\ 1.36/T & 0.55 \le T \le 4.0 \end{cases}$
Type III	$\frac{S_a}{g} = \begin{cases} 2.5 & 0 \le T \le 0.67 \\ 1.67/T & 0.67 \le T \le 4.0 \end{cases}$

3.4 Shear Demand on Shaft Staging

Shear Force due to Torsional Moment $V_T = V_B\left(\frac{e}{D_s}\right)$	= kN	
Design Horizontal Shear Force on the staging cross-section	$V_d = 0.5V_b + V_T$ = kN	$V_d = 0.5V_b - V_T$ = kN

3.5 Shear Capacity of Shaft Staging

Area of cross section through the opening of the shaft staging A_c	$A_c = 0.8 l_e t_s$ = m²	$A_c = 0.8(l_e - b)t_s$ = m²
Percentage of Longitudinal Reinforcement $\rho = \frac{100 A_{t\_st}}{A_s}$	=	=
For ρ% vertical steel in shaft wall from Table 19 of IS:456-2000, Design Shear Stress of Concrete τ_c	= MPa	= MPa
Shear Carried by Concrete $V_{uc} = \tau_c A_c$	= kN	= kN
Shear Carried by Steel V_{us}	$= 0.87 f_y A_{t\_st} \frac{0.8 l_e}{s_v}$ = kN	$= 0.87 f_y A_{t\_st} \frac{0.8 l_e - b}{s_v}$ = kN
Total Shear Capacity of Shaft Staging $V_{u,shaft} = V_{uc} + V_{us}$	= kN **> Shear Demand V_d**	= kN **> Shear Demand V_d**

3.6 Check for Overturning Moment

Over Turning Moment $M_{OT} = V_B \left(h_s + \frac{h_t}{2} \right)$	= kNm	= kNm
Restoring Moment $M_R = (W_{\text{tank}} + W_{\text{staging}} + W_{\text{foundation}}) \left(1 - \frac{2}{3} A_h \right) \frac{D_F}{2}$ where D_F, is diameter of the foundation	= kNm	= kNm
Factor of Safety = M_R / M_{OT}	=	=
Check	**> 1.5**	**> 1.5**