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EFFECTS OF SOIL CONDITION ON RESPONSE REDUCTION FACTOR OF ELEVATED RC WATER TANK

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Abstract — *in the present study, a RC framed staging elevated tank is considered to evaluate the response reduction factor with and without considering the effects of flexibility of soil. The existing elevated RC water tank is analyzed using displacement controlled non-linear static pushover analysis to evaluate the base shear capacity and ductility of tank with and without considering soil-flexibility. Three different types of soil conditions representatives of hard soil, medium soil and soft soil has been considered in this study. It is observed that flexibility of supporting soil has considerable effect on response reduction factor, time period and overall performance of water tank indicating that idealization of fixity at base may be seriously erroneous in soft soils.*

Keywords - Response *reduction factor, Soil-flexibility, Time period, Pushover analysis, and Elevated water tank.*

I. INTRODUCTION

Due to constant damage in recent earthquakes, it can be observed that the seismic behavior of a structure is highly influenced not only by the response of the superstructure, but also by the response of the foundation and the ground as well. Hence, the modern seismic design codes must emphasis on response analysis by taking into consideration a whole structural system including superstructure, foundation and ground. Conservatively, it is been considered that soil flexibility has an advantageous effect on the seismic response of a structure. Numerous design codes have recommended that the effect of soil flexibility can reasonably be neglected for the seismic analysis of structures. Most of the design codes use oversimplified design spectra, which attain constant acceleration up to a certain period, and thereafter decreases monotonically with period. The effect of soil flexibility makes a structure more flexible and thus, aggregate the natural period of the structure compared to the corresponding firmly supported structure. Moreover, considering the soil flexibility effect upturns the effective damping ratio of the system. The smooth idealization of design spectrum suggests smaller seismic response with the increased natural periods and effective damping ratio due to soil flexibility. This conventional simplification is valid for certain class of structures and soil conditions, such as light structures in relatively stiff soil. Unluckily, the assumption does not hold true always, but the different soil properties and its contact with superstructure can have a detrimental effect on the response of structure, and neglecting the effect of soil flexibility in the analysis may lead to unsafe design for both the superstructure and the foundation. The values of response reduction factor of elevated water tank adopted by difference codes/standards are summaries in Table-1.

Table 1 Values of R from different International codes

Codes	R value
IBC 2000 / FEMA 368	1.5 to 3.0
AWWA D110	2 to 2.75
ACI 350.3	2.0 to 4.75
IS:1893 – 2002 (Part – 2)RCC frame support	2.5

Patel and Shah investigated the formulation of key factors (i.e. over strength, redundancy, ductility) for seismic response modification factor of elevated water tank using ETABS software. They concluded that values assigned to R for a given framing system should vary between seismic zones.[6] Massumi and Tabatabaiefar studied ductile RC Moment-Resisting frames, as fixed-base structures once without soil interaction and the next time considering their soil interaction by direct method for different earthquake records. [7] Deepa and Nandakumar studied the Soil Structure Interaction (SSI) effects refer to the influence of the supporting soil medium on the behavior of the structure when it is subjected to various loads. It has been observed that increase in founding depth enhances the responses in the frame up to a certain depth. Soil structure interaction effects increases the responses in the frame up to the characteristic depth and decreases when the frame has been treated for the full depth. [8] Ismail discussed the importance of soil stiffness on the seismic performance of rigid structural frame system resting on it. The results showed that soil modulus have considerable effect on natural period and overall performance of structural system. [9] Livaoglu R studied the dynamic behavior of fluid–rectangular tank–soil/foundation system with a simple and fast seismic analysis procedure. The results showed that the displacements and base shear forces generally decreased, with decreasing soil stiffness. [10]

II. CONCEPT OF RESPONSE REDUCTION FACTOR

The liability of structures of civil engineering and especially structures such as elevated water tanks to seismic hazards is more drastic in developing countries with high seismicity, as compared to developed countries. The code provisions in IS: 1893(2000) allows that the damage to the structure is permitted in the case of sever shaking. Hence, the structure is designed for seismic force much lesser than that expected under strong earthquakes, if the structure were to remain linearly elastic. Thus, the code provides for a realistic force for an elastic structure and then divides that force by 2R. For example, if we consider a structure in Zone V, Z=0.36 gives a realistic indication of the ground acceleration. For T=0.3 s, Sa/g= 2.5 as per IS:1893 (Part1) 2002, which means that if the building remains elastic, it may experiences a maximum horizontal force equal to 90% of its weight (0.36x2.5= 0.90). If we use R factor of 5 and importance factor of 1, then we have to design the building for horizontal forces equal to 0.09 times the weight [0.90/ (2x5)]. It is clear from this example that the designer is going to design the building for only one-tenth of the maximum elastic force and hence should provide adequate ductility and quality control for good post-yield behavior.

In other words, the term R gives an indication of the level of over strength and ductility that a structure is expected to have. Thus, the structure can be designed for much lower force than is implied by the strong shaking by considering the following factors, which will prevent the collapse of the structure. The response reduction factor (R) is depends on Over strength (Rs), Ductility (Rμ), Redundancy (RR). According to ATC-19, it is described as

$$R = R_s * R_R * R_\mu.$$

Over strength factor (Rs) accounts for the yielding of a structure at load higher than the design load due to various partial safety factors, strain hardening, oversized members, confinement of concrete. Non-structural elements also contribute to the over strength. Ductility factor (Rμ) is a ratio of ultimate displacement or code specified permissible displacement to the yield displacement. Higher ductility implies that the structure can withstand stronger shaking without collapse. Redundancy factor (RR) depends on the number of vertical framing participate in seismic resistance. The change in R factor will be in accordance with its key components as shown in figure 1.

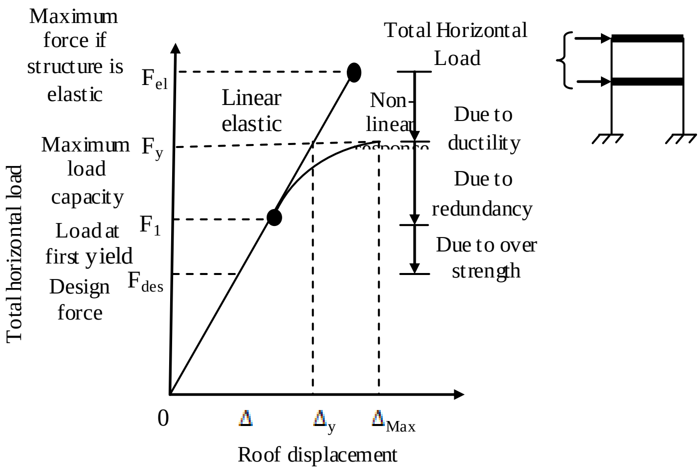

Fig.1 Understanding of Response Reduction Factor

III. IDEALIZATION OF SOIL

Maximum numbers of structures of the civil engineering hold one of its structural elements in straight contact with ground. When the lateral forces like earthquakes, act on these types of systems, the structural displacements and the ground displacements are dependent on each other. The process in which the response of the soil influences the motion of the structure and vice versa is termed as soil-structure interaction. A conservative structural design method neglects the soil flexibility and its effects on super structural response. To neglect the effects of soil flexibility is practical for light structures in comparatively stiff soil to soft soil such as low rise buildings and simple rigid retaining walls. The effect of soil flexibility becomes noticeable for heavy structures like power plants, high-rise buildings and elevated water tanks resting on relatively soft soil. The behavior of soil can be conveniently simulated using a set of elastic springs. The soil flexibility can be modeled as by providing translation, rocking and torsional elastic springs constant instead of rigidity of supports so as by providing soil properties in the model (FEMA 356). Various properties like soil elastic moduli, shear moduli, poison's ratio, unit weights, dimension of footings and compressibility characteristics is required for site-specific assessments of foundation bearing capacity and stiffness. The procedure and equations for the calculation of spring constants is given in Table-2a and Table-2b. Where, G=Shear modulus, v =Poisson's ratio, d=height of effective sidewall contact, h=depth of centroid of effective sidewall contact. The calculated spring constants using the formulas given in FEMA are considered as shown in Table-3.

Table 2a Elastic constants for Rigid Footing Spring Constraints

Degree of Freedom	Stiffness of Foundation at Surface
Translation along X-axis	$K_{x,sur} = \frac{GB}{2-\vartheta}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right]$
Translation along Y-axis	$K_{y,sur} = \frac{GB}{2-\vartheta}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right]$
Translation along Z-axis	$K_{z,sur} = \frac{GB}{1-\vartheta}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right]$
Rocking about X-axis	$K_{xx,sur} = \frac{GB^3}{1-\vartheta}\left[0.4\left(\frac{L}{B}\right) + 0.1\right]$
Rocking about Y-axis	$K_{yy,sur} = \frac{GB^3}{1-\vartheta}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right]$
Torsion about Z-axis	$K_{zz,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right]$

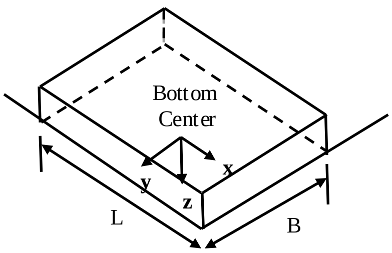

Table 2b Elastic constants for Rigid Footing Spring Constraints

Degree of Freedom	Correction Factor for Embedment
Translation along X-axis	$\beta_x = \left(1 + 0.21\sqrt{\frac{D}{B}}\right) - \left[1 + 1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right]$
Translation along Y-axis	$\beta_y = \beta_x$
Translation along Z-axis	$\beta_z = \left[1 + \frac{1}{21}\frac{D}{B}\left(2 + 2.6\frac{B}{L}\right)\right] - \left[1 + 0.32\left(\frac{d(B+L)}{BL}\right)^{2/3}\right]$
Rocking about X-axis	$\beta_{xx} = 1 + 2.5\frac{d}{B}\left(1 + \frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right)$
Rocking about Y-axis	$\beta_{yy} = 1 + 1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5 + 3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right]$
Torsion about Z-axis	$\beta_{zz} = 1 + 2.6\left(1 + \frac{B}{L}\right)\left(\frac{d}{B}\right)^{0.9}$

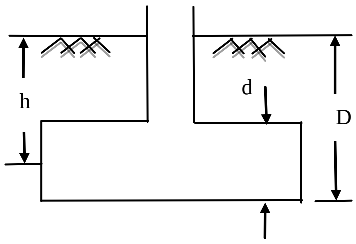

Table-3 Modulus of Elasticity, Poisson's Ratio and spring constants for different types of soils

Type of soil	Modulus of elasticity, E (kN/m^2)	Poisson's ratio (v)	Degrees of freedom	Spring constant for $2200m^3$ tank (kN/m)
Hard Soil	$2*10^5$	0.3	Translation about X-axis	74325.18
			Translation about Y-axis	74325.18
			Translation about Z-axis	92214.0
			Rocking about X-axis	254272.50
			Rocking about Y-axis	256309.40
			Rocking about Z-axis	370224.69
Medium Soil	$0.6 * 10^5$	0.33	Translation about X-axis	55200.00
			Translation about Y-axis	55200.00
			Translation about Z-axis	71584.62
			Rocking about X-axis	197390.77
			Rocking about Y-axis	198969.90
			Rocking about Z-axis	266872.32
Soft Soil	$0.15 * 10^5$	0.35	Translation about X-axis	22381.09
			Translation about Y-axis	22381.09
			Translation about Z-axis	29024.31
			Rocking about X-axis	80032.98
			Rocking about Y-axis	80673.25
			Rocking about Z-axis	108204.60

IV. DESCRIPTION OF WATER TANK

In present study, 'R' factor of RC elevated water tank having a capacity of 2200 m^3 is evaluated with and without considering flexibility of soil. The grade of the concrete is M30 for container, M25 for other components and steel reinforced of grade FE415 is used. Live load on roof slab is taken as $0.25kN/m^2$. The brief description of the considered elevated water tank is given in Table.4. The 3D idealization of tank with rigid base and elastic base is shown in figure 2 and 3.

Table-4 Details of water tank

Capacity(m^3)	2200
Zone	IV
Soil Type	Medium Soil
Container Length And Width	22.25
Height Of Container(m)	7
Wall Thickness(mm)	250
Top Slab Thickness(mm)	175
Bottom Slab Thickness(mm)	250
Height Of Staging(m)	18.4
Tie Beam Levels(m)	Plinth + 4.6
Column Size(dia)	600
No. & Dia Of Bars In Column(dia)	8-20mm
Plinth Beam(mm)	300*500
Braces Of Beam(mm)	300*500
Bottom Slab Beam(mm)	350*950
No. Of Column	24
Length Of Column(m)	4.6

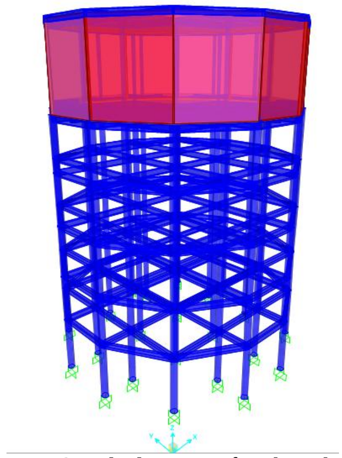

Fig.2: 3D idealization of tank with rigid base

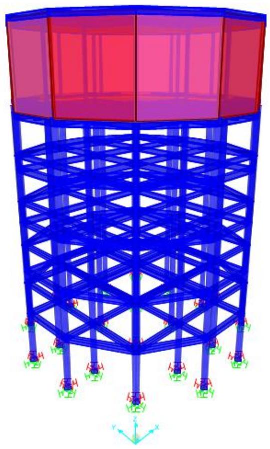

Fig.3: 3D idealization of tank with elastic base

V. ANALYSIS AND MODELING OF WATER TANK

SAP v15 is used to perform the nonlinear static pushover analysis of considered water tank. The RC beams and columns are modeled as three dimensional frame elements. Slabs are assumed to behave as rigid diaphragms. Damping ratio of 5 percent is assumed. Flexural hinge properties involve axial force, bending moment interaction (P-M) as the failure envelop and bending moment rotation (M-θ) as the corresponding load deformation relation. Flexure moment (M3) and axial biaxial moment (P-M3) are assigned in case of beam and column as hinge properties respectively. After assigning hinge properties to the structure, the static pushover cases are defined. Typically, the gravity loads are applied first and then subsequent lateral static pushover load cases are specified to start from the final conditions of the gravity pushover. In the gravity case, the structure is loaded with the dead load and 25% of the live load. The application of gravity loads is force-controlled whereas the application of lateral loads is displacement-controlled. The earthquake forces at each level in the tank are assigned as the load pattern for the lateral push applied to the structure.

From the analysis, the base shear versus roof displacement curve of the structure called static pushover curve, is obtained. The nonlinear static procedure requires prior estimation of target displacement. The target displacement serves as an estimate of the maximum displacement of the selected point in the subject structure during the design earthquake. The maximum limit for the roof displacement is specified as 0.004H, where H is the height of the CG of container from the base of the structure.

VI. RESULTS AND DISCUSSIONS

The considered water tank is analyzed using the nonlinear static analysis to obtain the pushover curve. The tank is subjected to step-by-step incremental lateral load up to lateral displacement of 0.004H at the CG of container. The base shear and roof displacement is recorded at every step. Due to plan symmetry of structure, the pushover analysis is carried out in X direction only. Hence, earthquake/lateral loads in tank full condition is given in X-direction only.

The figure 4 to 8 shows the pushover curves and their bi-linear representations (dotted lines) for various soil conditions.

Table-5 shows the values of seismic base shear, time period, R-factor and its key components over strength factor and ductility factor for 2200 m^3 water tank for rigid base and elastic base with three different soil conditions. It can be noticed that the quantities such as base shear, ductility factor, time period and response reduction factor changes considerably with the type of soil. It can be seen that as the soil tends to be elastic from rigid base to hard soil base, hard soil base to medium soil base, medium soil base to soft soil base the value of time period increases and value of base shear decreases significantly. It can also be viewed that the response reduction factor is the least with the soft soil to the other cases of tank considered.

Table- 5 Comparison ratio of Vb, T, Rs and R

Capacity of Water Tank	Type of soil	(1) Seismic Base Shear (kN)			(2) Time Period (s)		
		Without SSI	With SSI	Ratio	Without SSI	With SSI	Ratio
	Hard soil	1870	1860	0.99	1.78	1.9	1.07
	Medium soil		1740	0.93		1.94	1.09
	Soft soil		1520	0.81		2.12	1.19
		(3) Over Strength Factor			(4) Response reduction factor		
		Without SSI	With SSI	Ratio	Without SSI	With SSI	Ratio
	Hard soil	2.76	2.68	0.97	4.66	4.49	0.96
$2200m^3$	Medium soil		2.6	0.94		3.42	0.73
	Soft soil		2.45	0.89		3.26	0.70
		(5) Ductility factor					
		Without SSI	With SSI	Ratio			
	Hard soil	1.68	1.67	0.99			
	Medium soil		1.52	0.90			
	Soft soil		1.33	0.79			

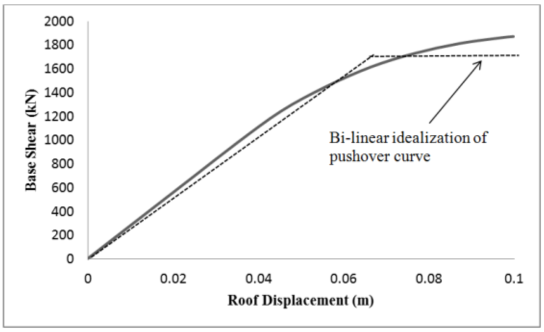

Fig.4: Pushover Curve of $2200m^3$ tank (Rigid base)

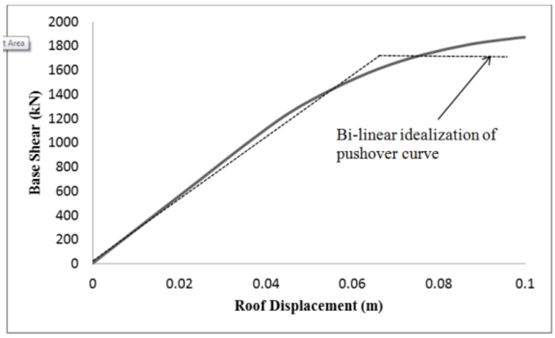

Fig 5: Pushover Curve of 2200m3 tank (Elastic base with hard soil)

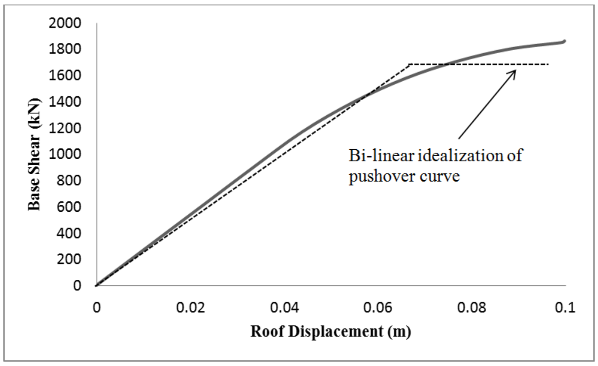

Fig 6: Pushover Curve for of 2200m^3 tank (Elastic base with medium soil)

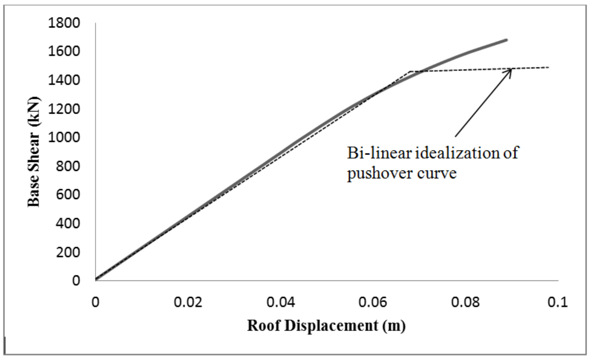

Fig 7: Pushover Curve of 2200m^3 tank (Elastic base with soft soil)

VII. CONCLUSIONS

In this study the response reduction factor (R) for RC framed staging elevated water tank having 2200 m^3 capacity is evaluated with and without considering soil-flexibility. The significant outcomes of present study are summarized as follows:

- The response reduction factor decreases while time period increases from fixed base to soft base. So it can be observed that avoidance of effect of soil flexibility might lead to mistaken and inappropriate results of flexibly supported RC frame structures.
- The effect of the soil-flexibility in case of soft soil increases the value of time period about 1.2 times in comparison to rigid base condition for the considered tank.
- The effect of the soil-flexibility in case of soft soil reduces values of R factor about 30% for the considered tank as compared to rigid base condition.
- The value of base shear is reduced up to 20% in case of soft soil to fixed base condition due to flexibility of soil. Here from the results we can observe that effect of soil flexibility is almost negligible in case of hard soil.

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