Seismic behavior of existing elevated water tanks resting on different type of foundations

P Kodanda Rama Rao¹, S R K Reddy², AHL Swaroop³ and K Nagarjuna.⁴

¹Vice Principal, ²Adjunct Professor ³Sr. Grade Assistant Professor, ⁴Assistant Professor
Department of Civil Engineering, SeshadriRao Gudlavalleru Engineering College, Gudlavalleru-521356, A.P., India.
Corresponding Author Email: Krr.pusala@gmail.com

Abstract. It has been well recognized that heavy structures built on soft soils, experience significant impact on seismic response, because of considerable foundation movements and hence, the effect of Soil-Structure-Interaction (SSI) can be a major factor while analyzing important structures like; nuclear power plants, elevated water tanks, chimneys, etc. against seismic forces. In general, elevated water tanks that were constructed on different type of soils in seismic regions, prior to the revision of seismic codes, must be checked on behavior and safety of such structures against earthquake loads as per present codes.

In this paper, two similar elevated R.C. circular water tanks, each of 4.0 lakh liters capacity supported by two types of foundations; one with circular ring raft below the columns of tank resting on sandy soils, and the other with circular ring raft supported by piles embedded in black cotton soils, are chosen for carrying out seismic analysis. In the analysis, the water tank is idealized as a system with three degrees of freedom, treating the staging of tank as one spring attached to the mass of the water tank and the soil is treated with two springs; one in horizontal and the other in rocking mode, both attached to the soil mass and the response parameters like; time periods, base shears and displacements are worked out against earthquake loads. Results indicate that, irrespective of type of foundation, the soil play important role on seismic response of elevated water tanks by virtue of their configuration with top heavy mass and slender staging; particularly displacements are found high when they rest on loose soils. According to the new guidelines provided in the revised IS 1893 (Part-1) 2016 code, SSI effect should be considered in seismic analysis when the structure rests on loose or soft soils.

Keywords: Shear modulus of soil, Mass matrix, Stiffness matrix, Damping, Time period, Base shear and Storey displacement.

1. Introduction

1.1. Present status of earthquake engineering in India

The seismicity conditions in India cannot be over emphasized. About 60% area of the country is considered prone to earthquakes of different intensities [1]. The major concern today is development of Indian seismic codes and building bye-laws, and enforcement of these codes in practice; particularly implementation of IS 1893 (Part-1) 2016 and IS 13290- 2016 [2,3]. In short span of about 20 years, India had experienced many moderate to great earthquakes during which damages occurred to many structures including elevated water tanks as shown in Figs.1&2.
1.2. Nature of Present Work

Many researchers carried out investigations [4,5] on seismic response of different structures under different soil conditions considering SSI effect. In the present investigation, the authors have chosen a typical elevated R.C. circular water tank with top heavy mass and slender staging supported by columns with periphery bracing system, and the analyses were carried out, when two such similar water tanks, that were constructed on different soils with different suitable foundations prior to the revision of seismic codes about twenty to thirty years back, and now if subjected to an expected earthquake in that region. MAT Lab and STAAD-PRO software are used to find out time periods, base shears and displacements for the two types of water tanks and the results are compared to establish the variation in these parameters when SSI effect is considered.

Elevated water tanks with huge quantity of water are critical and cause severe damage during earthquakes and may endanger drinking water supply, and sometimes may lead to another man-made hazard creating substantial economic loss. Since elevated water tanks are public utility structures and frequently used even in seismically active regions, dynamic behavior of such structures shall have to be investigated in depth.

2. Soil-structure-interaction

Soil stiffness and damping are important factors for dynamic modeling of the soil as they allow changes in properties of soil due to variation in strains, where in the response of soil influences the motion of the structure and the response of the structure influences the motion of the soil, which is referred as "Soil-Structure-Interaction" (SSI) [6,7].

A study on the response of elevated water tanks subjected to recent earthquakes has indicated that the variation between time periods of the structure and the supporting soil, is an important factor and hence, to evaluate the seismic response of a structure at a given location, the dynamic properties of combined soil-structure system shall be examined. For a structure founded on rock, the large stiffness of rock resists the rock motion very close to the free-field motion and hence the structure may be considered as fixed at the base. This assumption is justified for flexible structures resting on hard rock.
or stiff soils over which the foundation rests. However, stiff structures resting on flexible soils, the seismic response varies significantly due to SSI effect of flexible soils. After establishing this phenomenon of SSI effect by several researchers, in the revised IS 1893 (Part-1) 2016 code, a guideline is recommended in clause 6.1.5 that "Soil-Structure-Interaction refers to effects of the flexibility of supporting soil-foundation system on the response of the structure. Soil-Structure-Interaction may not be considered in seismic analysis of structures supported on rock-like material at shallow depth".

The present study made an attempt to justify the clause 6.1.5 of IS 1893 (part-1) 2016 code. In general, SSI will cause the natural frequency of combined soil-structure system lower than the natural frequency of structure itself when assumed fixed at the base. Also, due to radiation damping, the soil-structure system exhibits greater damping than that of the structure alone. In the present analysis, the damping is assumed as 5% for R.C structure, 10% for clay soils and 15% for sandy soils.

3. Problem chosen for the analysis

Two similar existing elevated R.C circular water tanks, each of 4.0 Lakh liters capacity supported by twelve circular columns, connected with three bracings at equal intervals along the height, which were constructed in seismic zone-3 before revision of IS 1893 (Part-I) code, having one foundation with circular ring raft resting on sandy soils, and the other foundation with circular ring raft supported by piles embedded in black cotton soils, are chosen for the study as shown in fig 3(a),3(b) & 3(c). The authors would like to investigate the seismic response of these two existing water tanks as per the present revised codes to compare the variation in seismic response parameters.

4. Methodology

4.1. Geo-Technical Properties

During earthquake motion, seismic waves travel through different layers of rock or soil media and these waves extend to the foundation and make the structure to vibrate. During these repetitive loadings, the response of the soil mostly controlled by the mechanical properties of the soil, such as shear wave velocity, damping ratio, poisson’s ratio, mass density and shear modulus.

4.2. Free Vibration Analysis

Using MAT Lab, free vibration analysis is carried out on the following three types of mathematical models of water tanks:

**Type-I:** Elevated R.C. circular tank supported by circular ring raft resting on sandy soils taking SSI effect into consideration.

**Type-II:** Similar elevated water tank as Type I, but resting on circular ring raft supported by vertical piles embedded in black cotton soils, considering SSI effect.

**Type-III:** Similar elevated water tank as Type I, but assumed to be fixed at the foundation level without considering SSI effect.

Getting information on static properties, which influence the dynamic behavior of these soils during an earthquake, has become much importance and the typical values evaluated are presented in Table-1 which are used for obtaining the soil spring constants.
Table-1: Types and properties of Soils

| Type | Description of Soil       | Shear Wave Velocity $V_s$ (m/s) | Mass Density $\frac{K\text{N}}{m^2}$ | Poission's Ratio $\nu$ | Shear Modulus $G = V_s^2 \times \rho$ [kN/m$^2$ x 10$^5$] |
|------|---------------------------|---------------------------------|-------------------------------------|----------------------|----------------------------------------------------------|
| I    | Sandy Soil                | 400                             | 1.90                                | 0.33                 | 3.0400                                                   |
| II   | Black Cotton or Soft Clay | 60                              | 1.73                                | 0.40                 | 0.0624                                                   |

4.2.1. Mathematical Modeling of Soil-Structure-Interaction System

a) Soil Model: Modeling of soil is represented with soil stiffness, mass and damping characteristics allowing dynamic changes in soil properties. The structure is assumed to rest on a uniform elastic half-space and soil- spring approach is used while modeling. Use of soil springs at the base of the structure, is the most accepted method of modeling in which the stiffness of soil springs play an important role acting in horizontal, rocking, torsional and vertical directions. Since the present structure is an elevated symmetrical circular water tank, torsional effect is neglected, and further, as the tank was already designed for gravity loads, vertical spring action is also ignored. Thus, in the analysis, the horizontal and rocking soil spring constants are only considered along with structure stiffness, treating it as one with three degrees of mass-spring-dashpot system.

In the present study, for Type-I structure with footing of circular ring raft resting on sandy soils, evaluation of equivalent linear soil spring constants is carried out using the equations suggested by Whitman & Richart (1967) [8]; and for Type-II structure resting on circular ring raft supported by piles embedded in black cotton soils, equivalent soil spring constants are worked out using Novak coefficients [9,10] and the values of both types are presented in Table-2.

![Fig. 3(a) Type-I Water Tank](image1) ![Fig. 3(b) Type-II Water Tank](image2) ![Fig. 3(c) Mathematical Model and Free Body Diagram](image3)
Table-2: Equations and Values for horizontal and rocking spring constants \((k_h \& k_\theta)\).

| S.No | Type of Spring Constant | Type-I Structure | Type-II Structure |
|------|--------------------------|------------------|------------------|
|      | Equation                  | Value x 10^5     | Equation          | Value x 10^5     |
| 1    | Horizontal \((k_h)\)     | \(\frac{32}{7-8}\nu\) Gr\_s \(\frac{G}{E_p} \cdot f_{x1}\) | 68.0 kN/m | \(\frac{E_p I_p}{r_0^3} \cdot f_{x1}\) | 4.75 kN/m |
| 2    | Rocking \((k_\theta)\)   | \(\frac{8 G r_o^3}{3(1-\nu)}\) | 1178 kN-m | \(\frac{E_p I_p}{r_0^3} \cdot f_{\theta1}\) | 12.86 kN-m |

Where,
- \(G\) – Shear Modulus of soil
- \(\nu\) – Poisson’s Ratio of soil
- \(r_o\) – Mean radius of circular ring raft

Soil Mass, \(m_o = 441\ kN\cdot s^2/m\)

Soil mass \((m_o)\) is calculated as per guidelines mentioned in IS 1893 (Part 2) 2016 considering weight of circular ring raft, weight of columns and connecting plinth beam below ground level, weight of soil above raft and 2/3 weight of staging.

b) **Structure Model:** In both type of structures, the geometry of water tank and staging is same. The tank has an internal diameter of 11.7 m with depth of water 3.75 m, the top dome being connected with ring beam. The entire system is supported by a staging with twelve numbers of 450 mm diameter columns, connected with a circular ring beam at the bottom. The columns are properly connected with three circular bracings at equal intervals along the height of the staging. Each type of tank is idealized as mass-spring dashpot system with one degree of freedom when it is assumed to be fixed at the base and with three degrees of freedom when SSI effect is considered. The top circular tank with water is lumped as top mass \((m_1)\) and stiffness of staging \((k_1)\) is worked out following IS 1893 code provisions. M-25 grade concrete and Fe-415 grade steel are used for all structural members.

Combination of soil model and structure model is presented in Figs 3a, 3b & 3c.
4.3. Method of Analysis

The fundamental time periods for the three types of water tanks are obtained from free vibration analysis using the equilibrium equations that are derived from mathematical model show in Fig. 3c. From free body diagram, the equilibrium equations are,

\[ m_1 \ddot{x}_1 + k_1 (x_1 - x_o - \theta H) = 0 \]  \hspace{1cm} I(a)

\[ m_0 \ddot{x}_0 + k_h x_o - k_1 (x_1 - x_o - \theta H) = 0 \]  \hspace{1cm} I(b)

\[ I_1 \ddot{\theta} + I_0 \ddot{\theta} + k_\theta \dot{\theta} - k_1 H (x_1 - x_o - \theta H) = 0 \]  \hspace{1cm} I(c)

Dividing I(c) by \( H \) throughout,

\[ \left( \frac{l_1 + l_o}{H} \right) \ddot{\theta} + k_\theta \frac{\theta}{H} - k_1 (x_1 - x_o - \theta H) = 0 \]

Let \( l_1 + l_o = l \)

\[ \therefore \frac{\ddot{\theta}}{H} + k_\theta \frac{\theta}{H} - k_1 (x_1 - x_o - \theta H) = 0 \]  \hspace{1cm} I(d)

Putting equations I(a), I(b) and I(c) in matrix form,

\[
\begin{bmatrix}
    m_1 & 0 & 0 \\
    0 & m_0 & 0 \\
    0 & 0 & \frac{l}{H^2}
\end{bmatrix}
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_0 \\
    \ddot{\theta}_H
\end{bmatrix}
+
\begin{bmatrix}
    k_1 & -k_1 & -k_1 \\
    -k_1 & k_1 + k_h & k_1 \\
    -k_1 & k_1 & k_1 + \frac{k_\theta}{H^2}
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_0 \\
    \theta H
\end{bmatrix}
= 0
\]

and is expressed in the form

\[ [m]\{\ddot{x}\} + [k]\{x\} = 0 \]  \hspace{1cm} (2)

Using the \( k_h \) and \( k_\theta \) values of Table-2, the mass and stiffness matrices for Types I & II water tanks are formulated and presented below.

For Type-I water tank model

\[
\begin{bmatrix}
    740 & 0 & 0 \\
    0 & 441 & 0 \\
    0 & 0 & 61.5
\end{bmatrix}
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_0 \\
    \ddot{\theta}_H
\end{bmatrix}
+10^5
\begin{bmatrix}
    0.612 & -0.612 & -0.612 \\
    -0.612 & 69.41 & 0.612 \\
    -0.612 & 0.612 & 8.79
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_0 \\
    \theta H
\end{bmatrix}
= 0
\]

For Type-II water tank model

\[
\begin{bmatrix}
    740 & 0 & 0 \\
    0 & 520 & 0 \\
    0 & 0 & 73.9
\end{bmatrix}
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_0 \\
    \ddot{\theta}_H
\end{bmatrix}
+10^5
\begin{bmatrix}
    0.612 & -0.612 & -0.612 \\
    -0.612 & 5.362 & 0.612 \\
    -0.612 & 0.612 & 0.702
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_0 \\
    \theta H
\end{bmatrix}
= 0
\]

For Type-III, when tank is assumed to be fixed at the base, it is idealized as single degree freedom system without SSI effect.

\[ m_1 = 740 \frac{KN-s^2}{m} \quad k_1 = 61200 \frac{KN}{m} \]
\[ \text{Time period, } T = 2\pi \sqrt{\frac{m_1}{k_1}} \]

\[ = 2\pi \sqrt{\frac{740}{61200}} = 0.691 \text{ sec.} \]

\[ T = 0.691 \text{ sec.} \]

Using above equations, free vibration analysis is carried out for Type-I and Type-II structures for obtaining the time periods and the results are tabulated in Table-3.

**Table-3** Time periods for Type-I and Type-II water tanks,

| Water Tank Type | Type-I water tank | Type-II water tank |
|-----------------|-------------------|--------------------|
| T(Sec)          | [0.719 0 0]       | [2.107 0 0]        |
|                 | [0 0.0527 0]      | [0 0.237 0]        |
|                 | [0 0 0.499]       | [0 0 0.170]        |

Using the above time period values, seismic analysis is carried out using STAAD-Pro for obtaining the storey shears and displacements at top of the water tank and at foundation level due to both horizontal and rocking soil springs and the results are presented in Tables 4 and 5.

**Table-4** Storey Shears for Types I & II water tanks,

| Type-I | Type-II |
|--------|---------|
| Q₁ = 134.56 kN | Q₁ = 136.52 kN |
| Q₂ = 44.41 kN | Q₂ = 46.31 kN |
| Q₃ = 4.60 kN | Q₃ = 20.56 kN |

Total Shear = 183.57 kN  
Total Shear = 203.39 kN

Where  
Q₁ = Shear at top mass level due to structure stiffness.  
Q₂ = Shear at foundation level due to horizontal stiffness of the soil.  
Q₃ = Shear at foundation level due to rocking stiffness of soil.

**Table-5**: Displacements for Types I and II water tanks,

| Type-I | Type II |
|--------|---------|
| Δ₁ = 2.380 mm | Δ₁ = 18.900 mm |
| Δ₂ = 0.021 mm | Δ₂ = 0.303 mm |
| Δ₃ = 0.166 mm | Δ₃ = 16.400 mm |

Total Δ = 2.567 mm  
Total Δ = 35.603 mm

Where  
Δ₁ = Horizontal displacement of mass (m₁) at top of the water tank (in mm)  
Δ₂ = Horizontal displacement at foundation level due to horizontal soil spring \( k_h \) (in mm)  
Δ₃ = Horizontal displacement at foundation level due to rocking spring of soil \( k_\varphi \) (in mm).
5. Results and discussions

5.1. Time Period

It is noticed that the fundamental time period of Type-I structure (0.719s), i.e. when water tank is resting on sandy soils, is less compared to the time period of Type-II structure (2.107s), when water tank is resting on loose soils. This attributes that the time period decreases with the increase of soil stiffness. It is also noticed that the time period (2.107sec) of Type-II structure resting on loose soil is more compared to the time period (0.691Sec) of water tank when SSI effect is not considered.

5.2. Storey Shears

From the results of seismic analysis, it is observed that the storey shear at top mass (m₁) level of water tank, is almost same in both cases. This is mainly because the mass of the water tank is same in both cases. It is also noticed that the variation of shear due to horizontal spring stiffness of soil in both cases is negligible. However, the shear due to rocking effect of piles in black cotton soil (20.56 kN) is found more than that of the shear taken by the raft resting on sandy soils (4.60kN). This attributes mainly due to the high stiffness of piles compared to the stiffness of soil and hence, the total base shear is observed more in Type-II structure resting on piles (203.39kN) than the shear obtained due to raft foundation resting on sandy soils (183.57kN).

5.3. Displacements

In general, it is noticed that displacements against earthquake loads are more when structure rests on loose soils compared to those when similar structure rests on stiff soils. In particular, the displacements due to rocking effect (θH), in loose soils contributes more compared to the displacements obtained due to structure stiffness or horizontal stiffness of the soil. This is justified from the results of Type II structure, which rests on loose soils, where the displacement at top mass level and at foundation level, are very high (18.3 mm and 16.4 mm respectively) due to the contribution from rotational effect of rocking spring of soil. Hence, irrespective of the type of foundation, displacements due to seismic loads are found more in case of loose soils compared to those when the structure rests on rock or stiff soils.

6. Conclusions drawn from the results of analysis

- Shear wave velocity influences significantly in changing the shear modulus of different soils. It is noticed that shear modulus increases proportional to the square of the shear wave velocity.
- Soil spring constants, both in horizontal and rocking modes, increase with the increase of stiffness of the soil.
- Fundamental time period of elevated water tank decreases with increase in stiffness of the soil and it also found less when SSI effect is not considered.
- In general, base shear increases with the increase of soil stiffness; however, it is noticed that loose soils absorb more shear than stiff soils.
- Under seismic conditions, it can be well established that displacements of structures resting on loose soils are more compared to those when they rest on rock or stiff soils. This attributes mainly due to the rocking effect of soil spring as the rotational displacement (θH) increases with decrease of stiffness of soil and also increases with height of the structure.
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