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Seismic Performance of Elevated Water Tank Considering Soil-Structure Interaction

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Abstract: Earthquakes are natural disasters that generate ground vibrations, often leading to some of the most destructive forces on Earth. These seismic events have the potential to cause severe damage to infrastructure, including lifeline facilities. Elevated storage reservoirs must remain operational even after a major earthquake. However, past seismic events have shown that elevated storage tanks frequently sustain damage or even collapse worldwide. The primary cause of such failures has been identified as the inadequate performance of their supporting frame staging. To ensure the seismic safety of these structures, it is essential to classify damage into quantifiable states. Among various parameters used to assess damage levels, the top drift of the frame staging serves as a reliable indicator.

This study evaluates the seismic vulnerability evaluation of reinforced concrete (RC) elevated water tanks frame staging with plain bar under different ground motion using fragility curve. Seven numbers of unscaled ground motion time histories are used to get the demand parameter in terms of drift. The drift capacity of the structure is determined from pushover analysis. A model of Intze type elevated water tank in Banke area is taken for analysis and analytical fragility curves are obtained for reservoir full, half full and empty case for fixed base, Spring base, and Half space condition. The effects of Fluid-Structure interaction and Soil-Structure in overall Fragility are also discussed.

Index Terms- Elevated water tank, Fluid-structure interaction, Soil-structure interaction,SAP2000, Time History Analysis, Pushover Analysis ,Fragility function.

1 Introduction

Earthquakes are among the most destructive natural forces on earth, often causing significant damage to human-made structures such as buildings, chimneys, towers, and critical public infrastructure like bridges, roads, dams, and irrigation facilities. They can also impact essential systems, including water supply and sewer networks, power plants, and industrial facilities. Additionally, earthquakes are known to trigger landslides, liquefaction, slope instability, and damage to earth and rock structures. These events not only result in loss of life and property but also profoundly affect the morale and resilience of communities.

Water stands as a fundamental element for the substance of all life forms. In Nepal, most municipalities have water supply which depends on elevated tanks for storage. Elevated water tank is a large elevated water storage container constructed for the purpose of holding a water supply at a height sufficient to pressurize a water distribution system. The construction of water tanks serves to capture, store, and distribute water to meet the needs of large communities. These liquid-retaining structures, commonly referred to as water tanks, have been in existence for nearly 50 years and are recognized for their efficiency and cost-effectiveness in both residential and commercial settings.

The seismic behavior of elevated water tanks differs significantly from that of other structures, with earthquake forces dominating their design in regions prone to seismic activity. Their susceptibility to damage during earthquakes is primarily due to the concentration of mass at the top of relatively slender supporting structures and limited exposed areas to the wind. The complexity of their behavior during seismic events is further compounded by interactions with soil and fluid. Analyzing these interactions with realistic parameters is essential for accurately assessing the behavior of elevated water tanks.

For the study purpose an elevated Intze type water tank has been considered, because intze tank is the most common type of concrete water tanks and widely used in Nepal for water storage. The reason for widely used is its shape, which helps to achieve an economy particularly for large storage capacity. To support intze shape container column with braces are provided. Figure 1.1 shows elevated intze type water tank.

Figure 1 Elevated water tank with frame type of staging

2 Liteature Review

1. Rai Durgesh C. (2002) discuss unfavorable features related to shaft supported elevated tanks in high seismic areas and suggest retrofitting technique to overcome with seismic deficiencies. Also, raised the issue related to the weaknesses of the current Indian code (IS 1893, 1984) of seismic design and analysis of structures against other international codes and ignorance of Housner's two-mass idealization.
2. Kaushik and Jain, (2007) presented performance of overhead water tanks of Port Blair during great Sumatra earthquake and tsunami of December 26, 2004. During the shaking, some of these tanks suffered substantial damages in the reinforced concrete (RC) staging due to plastic hinges developed at the bottom of all the columns and at the top of a few columns, while the container sustained no damage and staircase seems to have made the tank geometry unsymmetrical, and the tank sustained a torsional response.
3. S. C. Dutta et al., (2000a) aims to estimate the range of variation of torsion to lateral natural period ratio for usually constructed reinforced concrete elevated water tanks with frame-type staging for assessing their torsional vulnerability. Closed-form expressions for torsional and lateral stiffness of tank staging are derived and verified by standard finite element software.
4. Livaoğlu R. and Doğangün A., (2007a) considered two different types of supporting system, one is frame and other is cylindrical shell for the study. Seismic analysis were performed considering fluid-structure interaction and shows that, supporting system may considerably change the seismic behaviour of the elevated tanks. Elevated tank having frame supports the displacement response is more pronounced and has to be considered in the limit level. But for the shaft support this response is not similar.
5. Omidinasab F. et al., (2010) studied and analyzed, a reinforced concrete elevated water tank with 900 cubic meters under three pair of earthquake records in time history by using mechanical and finite-element modeling technique. Tank responses including base shear, overturning moment, tank displacement, and sloshing displacement under these three pair of earthquake records have been calculated, and result shows that the system responses are highly influenced by the structural parameters and the earthquake characteristics such as frequency content.
6. Gareane A. I. Algreane et al., (2011a) studied the soil and water behaviour of elevated concrete water tank under seismic load. The nonlinear modifications of the artificial seismic excitation are conducted through finite difference method software named NERA. Seven cases are analysed and compared with direct nonlinear dynamic analysis, mechanical models with and without soil structure interaction (SSI) for single degree of freedom (SDOF), two degree of freedom (2DOF), and finite elements method (FEM) models.

3 Statements of Problem

Nepal is located in one of the most seismically active zones in the world, making seismic safety a critical factor for all structures. Elevated water tanks, which are integral to the water supply systems in many Nepalese cities, must remain operational even after significant earthquakes to ensure a reliable water supply. These tanks are vital for public water distribution, especially in developing regions. Known as lifeline structures, they provide not only drinking water but also an essential supply for firefighting and other emergency needs following seismic events. In Nepal, most elevated water tanks, whether already built or currently under construction, are supported by frame structures.

In Nepal's major cities, many elevated water tanks were built before the 1990s and are considered to be constructed following the codes in place at the time. These structures commonly use plain bars made of mild steel as reinforcement. As essential facilities, ensuring their seismic resilience is crucial. To secure their safety in future earthquakes, it is necessary to assess the seismic vulnerability of each tank and implement appropriate interventions where needed.

The seismic performance of elevated liquid storage tanks has been underexplored. This approach overlooks the effects of soil-structure interaction, which can lead to significant discrepancies in design particularly on Medium soil sites like those in Western region, potentially resulting in either over or under design. For existing elevated tanks, fragility curves provide the conditional probability of structural failure, indicating the likelihood that the structure reaches a predefined limit state based on an earthquake intensity. This information is crucial for identifying deficiencies in current structures, allowing for targeted strengthening to enhance earthquake resilience.

4 OBJECTIVES OF STUDY

This research aims to study seismic performances of elevated water tank filled, half-filled and empty conditions considering soil-structure interaction (SSI) and fluid-structure interaction (FSI) effects of the elevated water tank

5 DIMENSIONS AND MODELS

Parameters	Details
Capacity of the tank	450 m3
Unit weight of concrete	25 kN/m3
Unit weight of Water	9.81 kN/m3
Grade of concrete fck	30 N/mm2
Grade of Steel fy	415 N/mm2
Thickness of Top Dome	0.1m
Rise of Top Dome	1.6 m
Size of Top Ring Beam	0.25 × 0.30 m
Diameter of tank container	9.95
Height of Cylindrical wall	4.6 m
Thickness of Cylindrical wall	0.2 m
Size of Middle Ring Beam	0.85 m × 0.6 m
Convective spring	0.45 m × 0.45m
Rise of Conical dome	2.6 m
Thickness of Conical dome	0.475 m
Rise of Bottom dome	1.5 m
Thickness of Bottom dome shell	0.3 m
Size of Bottom Circular girder	0.5 × 0.3
Distance between intermediate bracing	4 m
Height of Staging above Foundation	20 m
Number of Columns	6
Number of Peripheral Bracings Level	3
Distance between bracing	4 m
Size of Columns	0.575 m× 0.575m

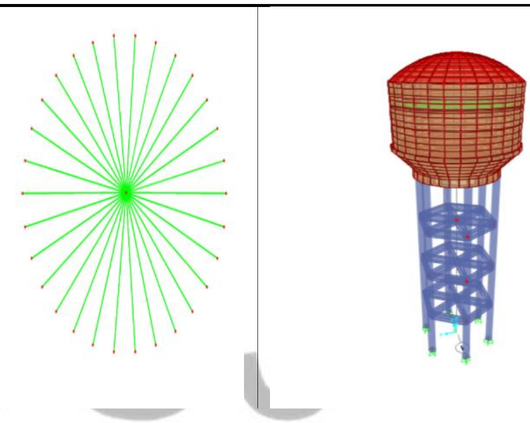

Figure 2: Spring Mass Model of Tank

6 DATA PROCESSING PROCEDURES

For Data Processing SAP2000 software and IS 1896:2016 code is used for Time History Analysis and Pushover analysis is done for full, half full and empty condition can be modeled.

Data analysis is done by the following steps

Step 1: Preparation of 2-D and 3-D model of elevated water tank with different geometry like Basic, Radial bracing and Cross bracing and their material properties.

Step 2: Assigning of Different load to the model

Step 3: Estimation of design lateral force on building using IS 1896:2016.

Step 4: Analysis of the models with Fixed based, spring based and half spaced based systems Non-linear Time History Analysis and push over analysis.

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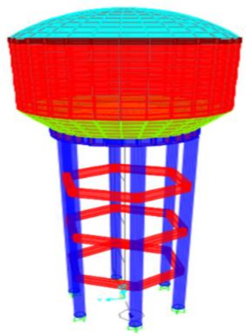

Figure 3: FE model of elevated water tank with basic type

7 RESULTS

For this study, the seismic performance of elevated water tank of Basic, Radial bracing and Cross bracing pattern research work, with considering fixed based, spring based and half spaced based condition with full, half full and empty condition. The formulation and modeling were carried out in SAP2000. The Non-Linear Time History and Pushover analysis approach were used to model elevated water tank in which the superstructure was supposed to be linearly elastic and spring system was non-linear.

In this section, the analysis results in terms of fundamental modal time period, fundamental frequency, Overturning moment, Top displacement, Sloshing displacement, Base Share were discussed.

7.1 Seismic Parameters Results of Fixed base, Spring based and half spaced based Models Due to THA and POA

7.1.1 Top Displacement

Figure 4 shows the top displacement of elevated water tanks under different staging patterns and water level conditions (Empty, Half, and Full) under fixed based condition. Cross bracing shows the lowest top displacement across all water levels, with the Half-filled condition (0.0516 m) being the most stable. Radial bracing performs better than Basic, which shows the highest displacement. Overall, bracing patterns significantly reduce displacement, especially under Full water level condition.

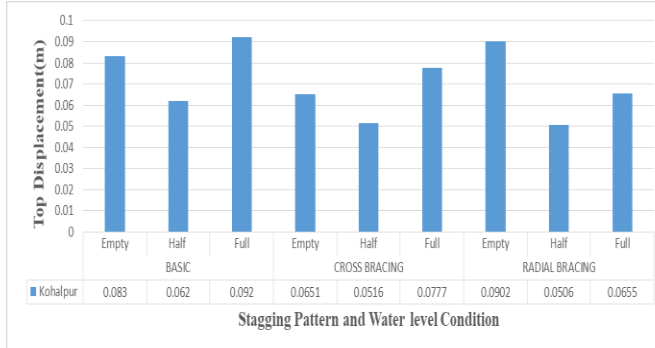

Figure 4: Comparison of Top Displacement v/s different staging patterns and water level under fixed based condition

7.1.2 Overturning Moment

Figure 5 shows the Overturning Moment of elevated water tanks under different staging patterns and water level conditions (Empty, Half, and Full) under fixed based condition. Radial bracing is the most effective, with the lowest overturning moment observed at 20136.2 KN-m Half full condition. Basic staging has the highest overturning moment, especially under full tank conditions (36991.5 KN-m). Cross bracing performs moderately, reducing overturning moments compared to Basic staging.

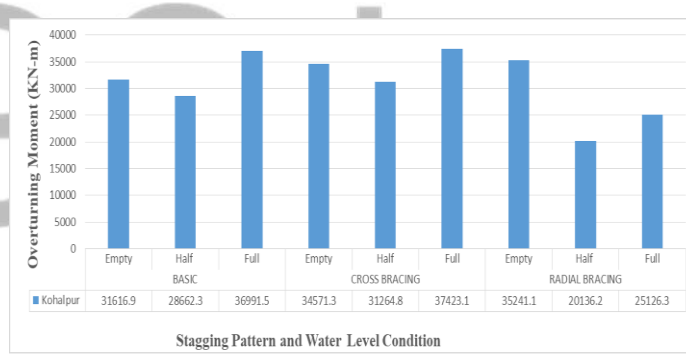

Figure 5: Comparison of Top Displacement v/s different staging patterns and water level under fixed based condition

7.1.3 Sloshing Displacement

Figure 6 shows the Sloshing Displacement of elevated water tanks under different staging patterns and water level conditions (Empty, Half, and Full) under fixed-based conditions. The chart shows that sloshing displacement is highest in the half-filled condition of Radial bracing. Cross bracing is the most effective staging pattern, significantly reducing displacement compared to Basic and Radial Bracing. The half-filled condition is the most critical, requiring focused structural improvements for stability.

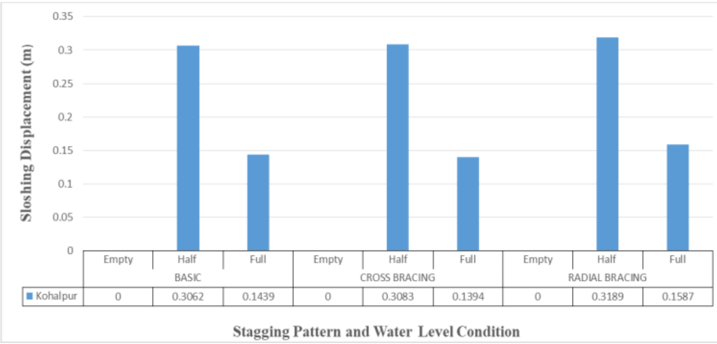

Figure 6: Comparison of Sloshing Displacement v/s different staging patterns and water level under fixed-based condition

7.1.4 Base Share

Figure 7 shows the Base Share of elevated water tanks under different staging patterns and water level conditions (Empty, Half, and Full) under fixed-based condition. The chart show Cross bracing has the highest base shear, ensuring strong seismic resistance at full condition (1972.35 kN). Radial bracing has the lowest values, especially at half water levels (1040.36 kN).

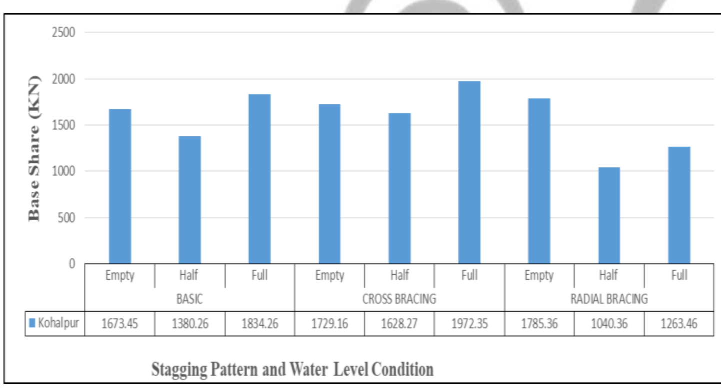

Figure 7: Comparison of Base Share v/s different staging patterns and water level under fixed-based condition

7.1.5 Maximum Model Fundamental Frequency

Figure 8 shows the time period of elevated water tanks under different staging patterns and water level conditions (Empty, Half, and Full) under different based condition. The chart shows basic with increasing base shear as water levels rise, led by Kohalpur (Full: 1834.26 kN).Cross bracing has the highest base shear, ensuring strong seismic resistance Full: 1972.35 kN).

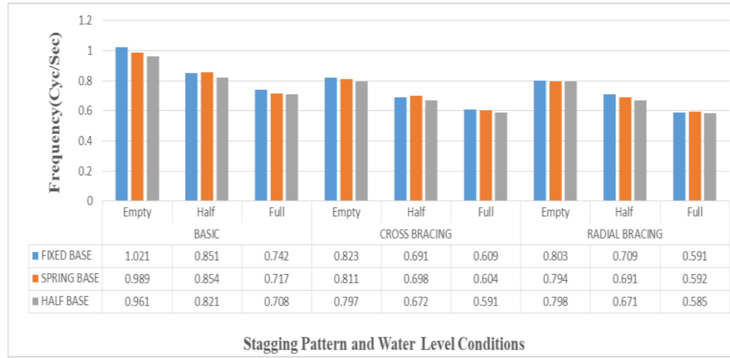

Figure 8: Comparison of Frequency v/s different staging patterns and water level under different base conditions

7.1.6 Maximum Model Fundamental Time period

Figure 9 shows the frequency of the structure under different base conditions (Fixed, Spring, Half) and water levels (Empty, Half, Full) for three staging patterns (Basic, Cross Bracing, and Radial Bracing). Fixed Base consistently shows the highest frequency, with Basic having the highest at Empty (1.021) and Radial Bracing the lowest at Full (0.591). Spring Base and Half Base show a decrease in frequency compared to Fixed Base, with Spring Base slightly higher than Half Base.

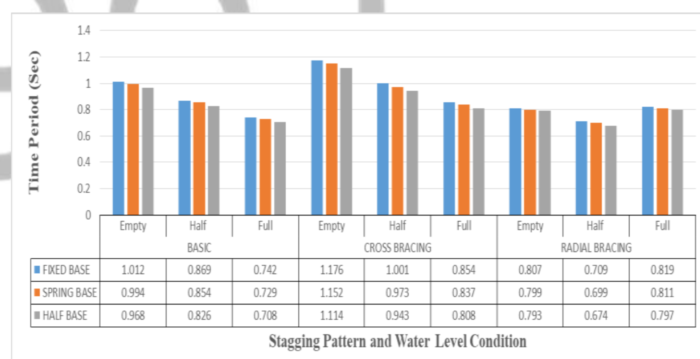

Figure 9: Comparison of time period v/s different staging patterns and water level under different base condition

8 CONCLUSION

1. The reservoir full case is more vulnerable than half full and empty cases with probability of failure more than 0.12%, 1.74%, 12.98%, 26.81% and more than 0.26%, 3.46%, 25.97%, 47.8% for slight, moderate, extensive and complete damage states at fixed base condition at severe level of shaking.

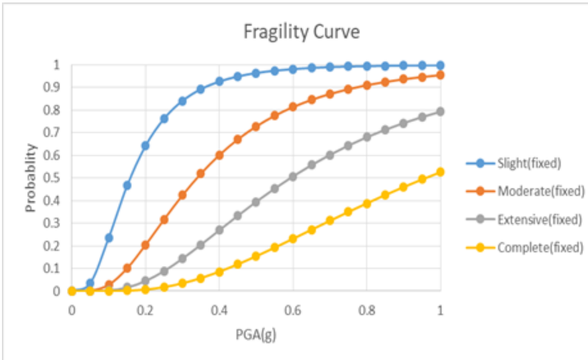

Figure 10: Fragility curve for full case of fixed based condition

2. The introduction of soil flexibility increases the fundamental period of the structure by 9.38%, 12.53% and 12.60% for reservoir full, half full and empty cases respectively and there is almost no effect on convective mode.

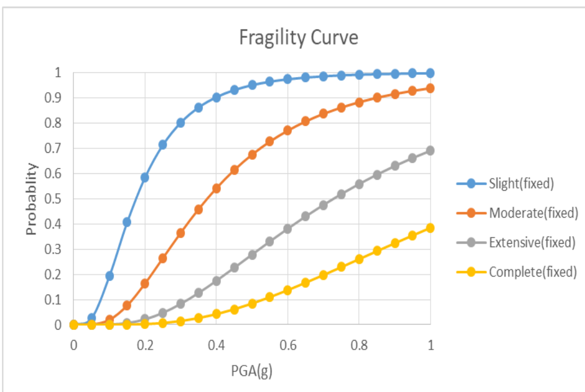

Figure 11: Fragility curve for half full case of fixed based condition

3. SSI amplify the probability of exceeding the extensive and complete damage by (0.63%,0.94%), (6.16%, 4.52%) and (20.95%,13.07%) at severe level of shaking for full case, half full case and empty case respectively. Hence ignoring effect of soil flexibility leads to under-estimation of failure probability which leads the decision maker towards inaccurate decision of strengthening and retrofitting.

4. The acceptable Sa for target 5% probability of failure for frame staging of elevated water tank are found to be 0.029g, 0.06g, 0.18g and 0.32g for slight, moderate, extensive and complete damage respectively.

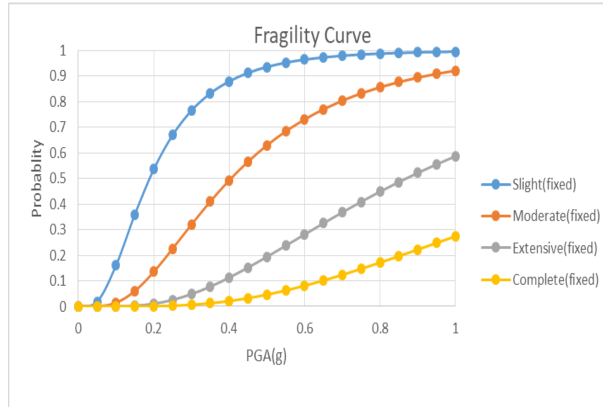

Figure 12: Fragility curve for half full case of fixed based condition

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