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Original Article

Seismic Response of Underground Rectangular Water Tank Structures by Nonlinear Static Analysis

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Abstract *- During earthquakes, the most prone to damage or collapse are concrete structures. The structure's behavior during earthquakes depends mainly on its shape, size, and geometry. An attempt is made to understand the seismic response of the Underground Rectangular Water tank structure subjected to Nonlinear static loading. To predict the seismic response of building structures during severe earthquakes, Pushover analysis has been frequently utilized. It needs to be investigated whether it applies to reinforced concrete Underground Rectangular Water tank structures. This paper attempts a pushover analysis of the Underground Rectangular Water tank structure. The most prominent and versatile finite element analysis software SAP2000 is used to model and analyze Underground Rectangular water tank structures to perform Pushover analysis. Various parameters of a Pushover analysis of an Underground Rectangular water tank are also summarized to understand the behavior of the Underground Rectangular water tank structure.*

Keywords *- Underground water tank, Nonlinear static analysis, Pushover analysis seismic behavior.*

1. Introduction

The Nonlinear static analysis method, also known as Pushover analysis, is widely accepted for predicting nonlinear structural behavior. When the structures are built in the most severe seismic zone (Zone-V), they are most prone to seismic loading. Thus, it is mandatory to predict its structural behavior to ensure high performance and long life.

The manual nonlinear static (pushover) analysis is a very tedious task with a high possibility of calculation errors affecting the structure analysis. The process has become much easier with the availability of modern tools for structural analysis and design. Thus, SAP2000 software is used to carry out this Nonlinear static analysis of the Underground water tank structure subjected to seismic loading.

In SAP 2000, the force pattern utilized in the nonlinear static analysis might be based on a uniform acceleration in a specified direction, a specified mode shape, or a user-defined static load case. SAP 2000 will assign a force pattern proportional to the translational mass distribution in the relevant direction on applying a uniform acceleration.

This paper attempts to understand the behavior of an Underground Rectangular Water tank with a capacity of 72000 litres subjected to seismic loads using advanced finite element software SAP2000 V14. The region where the

Underground Rectangular water tank is located is assumed as zone V as per IS 1893 (Part – 1): 2016. The Underground Rectangular water tank comprises four major sections: top slab, long wall, short wall, and base slab. The surrounding earth material supports the Underground Rectangular Water tank structure. For the analysis of the Underground Rectangular water tank having 72000m capacity, the nonlinear static (pushover) analysis method is used. To perform the pushover analysis, the lateral loading pattern used is unit acceleration in both the X and Y directions. With a set of ground motions, a finite element software, SAP2000 V14, performs a nonlinear time-history analysis of the MDOF (Multi-degree of Freedom) underground Rectangular Water tank model. Table 1 lists the details of the modelled structure. Figure 1 depicts the simulated structure.

2. Modelling of Underground Rectangular Water Tank Structure

The material models' precision significantly impacts the reliability of nonlinear structural components, as the reinforced concrete members' nonlinear behavior is derived directly from the nonlinear stress-strain connection between steel and concrete fibers. Nonlinear Static Analysis of Underground water Tanks Reinforced concrete sections are made of three materials: unconfined concrete, confined concrete, and reinforcement steel. The Steel material model represents reinforcing bars. It is a kinematic hardening bilinear steel material model.

Table 1. Details of Parameters for Underground Rectangular water tank with 72000 litres capacity

DESCRIPTION	PARAMETER
Length of tank	6000mm (6m)
Width of tank	4000mm (4m)
Height of tank	3000mm (3m)
The thickness of the Base Slab	150 mm
The thickness of the Top Slab	275 mm
The thickness of Long Walls	275 mm
The thickness of Short Walls	275 mm
Grade of Concrete	M-20
Grade of Steel	Fe-415
Unit Weight of Soil	18 KN/m^3
Bearing capacity of Soil	250KN/m^2
Soil type	Type-II
Seismic zone	Zone-V

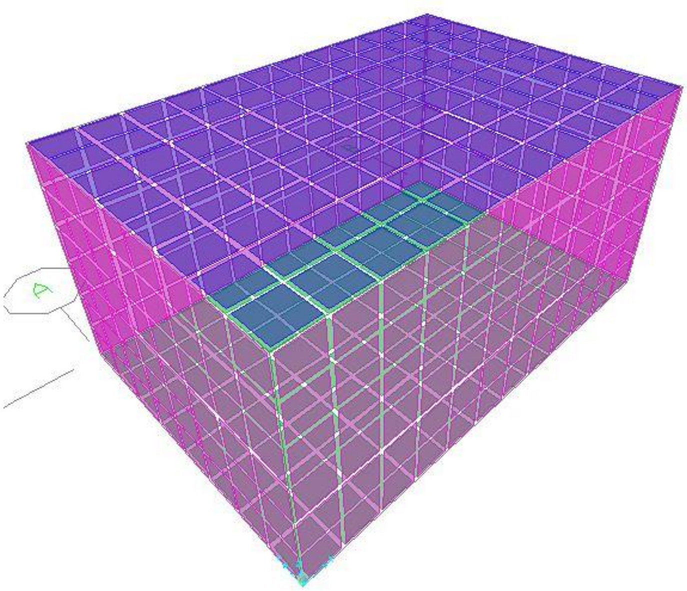

Fig. 1 Model of Underground Rectangular Water tank with 72000 litres capacity

The stress-strain relationship of core concrete, which is contained with transverse reinforcement bars, differs from that of unconfined (cover) concrete. The member's strength and elasticity can be improved using confinement. As a result, distinct material models will be used for confined and unconfined concrete.

3. Free Vibration Analysis

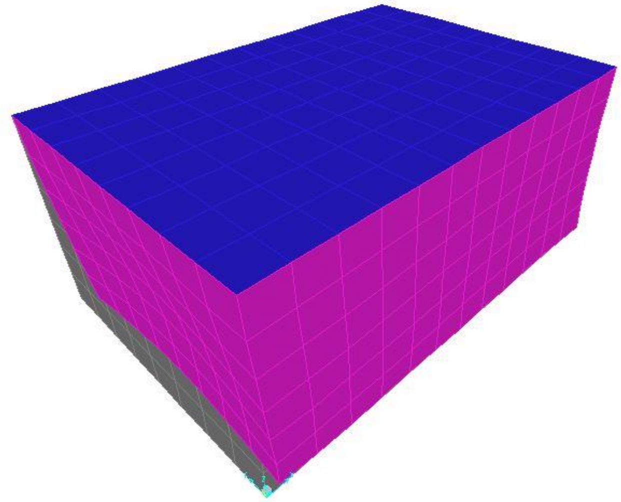

Fig. 2 Seventh mode shape of Underground Rectangular water tank with 72000 litres capacity

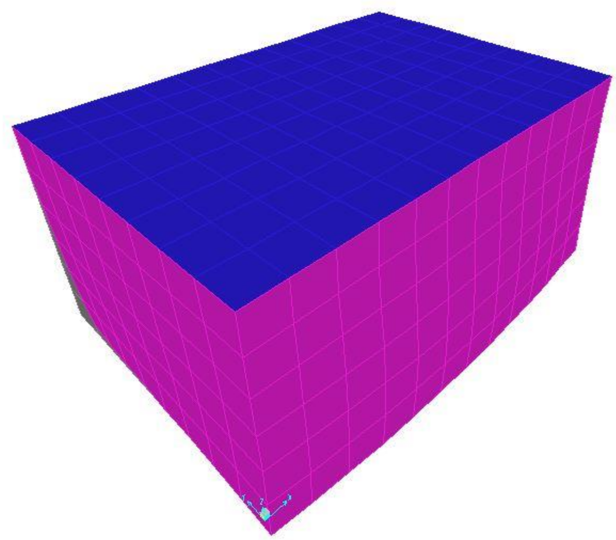

Fig. 3 Third mode shape of Underground Rectangular water tank with 72000 litres capacity

The free vibration analysis of the Underground water tank is performed for 12 modes to get the first important insight into dynamic structural properties. The modal characteristics of the Underground water tank are presented in the X, Y, and Z directions in Table 2 for the first 12 modes. The most prominent modes in the X and Y directions are Mode 7 and 3, respectively. The modal participation observed in X, Y, and Z directions are 0.76, 0.76, and 0.064. The deformed shape of the seventh mode of the Underground Rectangular Water tank is shown in Fig. 2, and that of the third mode is shown in Fig. 3.

Table 2. Modal characteristics of Underground Rectangular water tank with 72000 litres capacity

Mode	Period (s)	Frequency (Hz)	Modal Participating Mass Ratio		
			X	Y	Z
1	0.304	3.283	1.341×10^{-18}	3.872×10^{-18}	**0.34**
2	0.236	4.224	4.855×10^{-11}	6.17×10^{-13}	0.046
3	0.197	5.062	9.73×10^{-17}	**0.76**	1.802×10^{-17}
4	0.175	5.688	8.445×10^{-5}	2.757×10^{-16}	3.3×10^{-15}
5	0.149	6.679	1.712×10^{-8}	1.963×10^{-12}	1.339×10^{-5}
6	0.136	7.350	1.5×10^{-17}	5.091×10^{-4}	1.635×10^{-15}
7	0.135	7.402	**0.76**	1.724×10^{-15}	1.783×10^{-15}
8	0.109	9.125	2.587×10^{-15}	5.353×10^{-14}	0.064
9	0.101	9.835	6.521×10^{-15}	2.678×10^{-14}	1.24×10^{-3}
10	0.101	9.883	4.239×10^{-12}	2.385×10^{-9}	5.422×10^{-4}
11	0.101	9.899	9.951×10^{-17}	1.429×10^{-15}	4.76×10^{-15}
12	0.092	10.814	1.219×10^{-15}	0.01481	7.35×10^{-14}

4. Nonlinear Static Analysis of Underground Rectangular Water Tank Structures

When doing a pushover study, a structure is subjected to a monotonically increasing pattern of lateral loads, which reflects the inertial forces that the structure would feel if subjected to ground shaking. Various structural parts may yield consecutively under steadily increasing loads. As a result, the structure loses rigidity as each event occurs. A typical nonlinear force-displacement relationship is derived via a pushover analysis. Pushover analysis is performed for unit acceleration in two directions, i.e., X and Y. Unit acceleration is applied at the center node of the long wall and short wall.

5. Results and Discussion

Pushover analysis produces capacity curves, capacity-demand curves, and performance points. To understand the behavior of Underground water tank structure, parameters like displacements, membrane forces, membrane stresses, and shell layer stresses are determined. Maximum positive and negative values are stated for all these parameters.

5.1. Capacity Curve

The results of a nonlinear static analysis on an Underground Rectangular water tank structure intended for seismic loads are presented. The size of the members is increased to meet the structure's capability and demand. Figures 4 and 5 illustrate the capacity curves for the Underground Rectangular water tank construction in the X and Y directions. The values of base shear and displacement at the yield point are shown in Table 3.

Table 3. Parameters of Underground Rectangular Water Tank Structure by pushover analysis

Pushover Analysis	Yield Point		Initial Stiffness	Final Stiffness
	V_y (KN)	D_y(mm)	K_1 (kN/m)	K_2 (kN/m)
In X -direction	4235.556	0.0014	2830033.8	1966873.49
In Y -direction	4853.874	0.0031	1535618.3	1093360.23

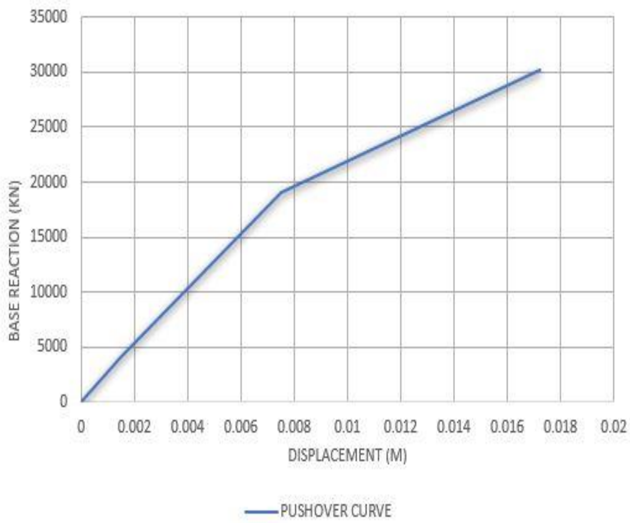

Fig. 4 Capacity Curve for Underground Rectangular Water Tank Structure designed for Seismic loads in the X direction

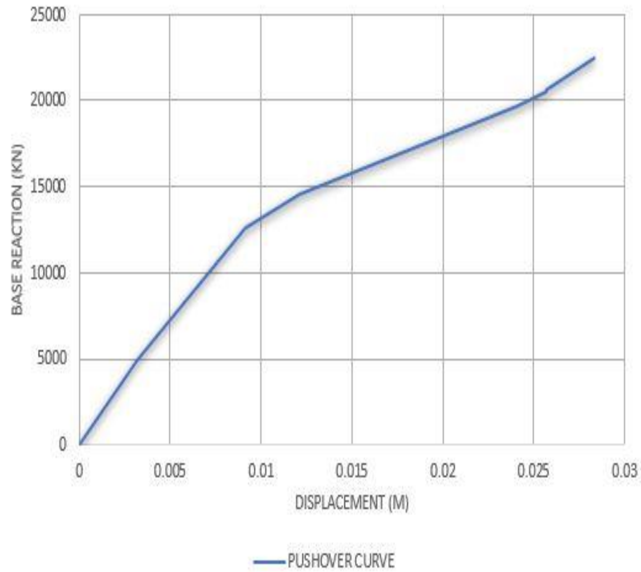

Fig. 5 Capacity Curve for Underground Rectangular Water Tank Structure designed for Seismic loads in the Y direction

5.2. Capacity Demand Curve and Performance Point

Pushover analysis creates capacity curves in the X and Y directions. After that, the capacity curves are converted into capacity spectrum curves. The junction point of the capacity and demand spectrum curves is designated the performance point. Between Spectral Displacement, Sd (m), and Spectral Acceleration, Sa (g), and Capacity Demand Curves are plotted are shown in Figure 5 and Figure 6 for X and Y directions, respectively. The Acceleration Displacement Response Spectra (ADRS) method obtains the demand curve. The procedure adopted is as mentioned in ATC 40. The Underground Rectangular Water tank Structure's response to Seismic loads by Pushover analysis is tabulated in Table 4.

Table 4. Response of Underground Rectangular Water tank Structure designed for Seismic loads by Pushover analysis

Pushover Analysis	Yield Point		Performance Point		Performance Point	
	V_y (KN)	D_y(mm)	V (kN)	D(m)	S_a (g)	S_d(m)
In X -direction	4235.556	0.0014	954.689	0.0003	0.665	0.0002
In Y -direction	4853.874	0.0031	1175.704	0.0008	0.798	0.0005

Table 5. Displacement in Underground water tank due to seismic loads

Parameters	Maximum Values	Pushover Analysis		
		X-direction	Y-direction	Z-direction
Horizontal Displacement in X-Direction, U_X (m)	(+)	**0.0245**	0.0064	0.0018
	(-)	-0.0002	-0.0063	-0.0063
Horizontal Displacement in Y-Direction, U_Y (m)	(+)	0.0119	**0.0432**	0.0031
	(-)	-0.0119	-0.0003	**-0.0517**

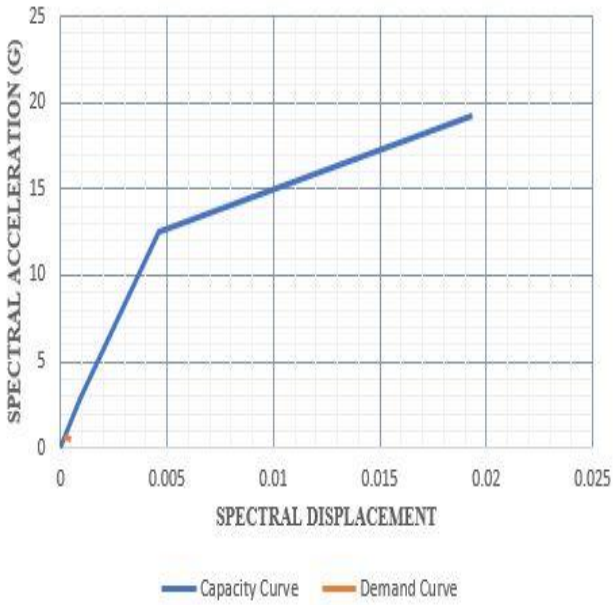

Fig. 5 Capacity-Demand Curves for Underground Rectangular Water tank Structure designed for Seismic loads in the X direction

5.3. Displacement

The maximum and minimum values of nodal displacements for pushover analysis cases are tabulated in Table 5. The maximum deflection is 0.0245 m in the X direction, 0.0432 m in the Y direction, and 0.0517 m in the Z direction.

5.4. Membrane forces

The two-membrane normal resultant forces are F11& F22, and the membrane in-plane shear force per unit length is F_{12} which collectively makes up the internal membrane (in-plane) forces. The two bending moments per unit length are M_{11} & M_{22}, the twisting moment of the shell cross-sections per unit length is M_{12}, and the two transverse out of plane shear forces per unit length are V_{13} & V_{23} which collectively make up the bending forces field. The maximum and minimum values of the Membrane Forces per unit length for the nonlinear static analysis case of the Underground Rectangular Water tank are tabulated in Table 6.

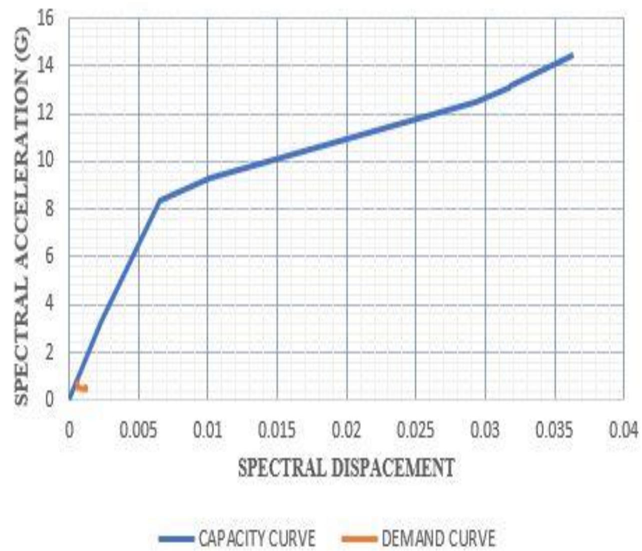

Fig. 6 Capacity-Demand Curves for Underground Rectangular Water tank Structure designed for Seismic loads in the Y direction

Table 6. Maximum membrane forces and Bending Moments for Pushover analysis in different structural members of Underground Rectangular water tank

Parameters	Max. Values	Top Slab	Long Wall	Short Wall	Base Slab
Membrane forces in the X direction, F_{11} (kN/m)	+	20.189	428.745	789.866	731.147
	-	-101.239	-17.738	-88.257	-
Membrane forces in the Y direction, F_{22} (kN/m)	+	12.039	**5070.456**	**1636.717**	795.786
	-	-135.882	-255.843	-197.667	-
In-Plane Shear Forces, F_{12} (kN/m)	+	**164.919**	3440.700	1573.721	**1555.278**
	-	-20.079	-24.357	-50.263	-0.925
Out of Plane Shear Force, X direction, V_{13} (kN/m)	+	21.923	118.496	275.456	182.651
	-	-20.343	-4.984	-10.365	-170.844
Out of Plane ShearForce, Y direction, V_{23} (kN/m)	+	26.906	68.734	277.423	214.751
	-	-26.434	-44.225	-40.520	-174.917
Bending Moment in X direction, M_{11} (kN-m/m)	+	4.711	55.545	37.631	65.687
	-	-8.409	-3.594	-2.724	-28.766
Bending moment in the Y direction, M_{22} (kN-m/m)	+	10.224	28.095	59.105	106.193
	-	-11.884	-45.322	-36.357	-30.542
Twisting Moment, M_{12} (kN-m/m)	+	5.577	73.860	159.106	107.671
	-	-3.848	-13.486	-25.350	-61.011

5.4. Membrane Stresses

The basic shell element stresses are denoted as S11, S22, S12, S13, and S23. The membrane stress, S11, and S22 are the direct stresses in the X and Y directions, respectively. The membrane stress, S12, is the shear stress. The plate stresses, S13 and S23, are the transverse shear stresses in the X and Y directions. The maximum and minimum values of the Membrane Forces per unit length for nonlinear static analysis cases are tabulated in Table 7.

Table 7. Maximum Membrane Stresses for Pushover Analysis in different structural members of Underground Rectangular water tank

Parameters	Max. Values	Top Slab	Long Wall	Short Wall	Base Slab
Membrane Direct Stress, X direction, S_{11} (kN/m^2)	+	1509.583	1937.719	3857.91	1311.413
	-	-1590.614	-157.525	-215.215	-1133.572
Membrane Direct Stress, Y direction, S_{22} (kN/m^2)	+	2250.236	**17406.769**	5531.380	1476.146
	-	**-3358.511**	3329.795	-2861.211	-2758.518
Membrane Shear Stress, S_{12} (kN/m^2)	+	1864.171	14592.285	**18292.256**	**11050.95**
	-	-1111.847	-2481.509	-427.974	-5801.258
Plate Transverse Shear Stress, X direction, S_{13} (kN/m^2)	+	2.419	8.800	20.213	13.442
	-	-2.313	-0.393	-0.887	-12.612
Plate Transverse Shear Stress, Y direction, S_{23} (kN/m^2)	+	3.037	4.964	20.279	15.644
	-	-2.984	-3.322	-2.951	-12.757

6. Conclusion

Pushover analysis of the Underground Rectangular water tank with a capacity of 72 cum has been conducted using advanced finite element software SAP2000 V14. Underground Rectangular Water tank Structure is designed as per IS 1893- Part I (2002), Criteria for earthquake resistant structure. The region where the Underground water tank is located is assumed as zone V, and medium soil type as per IS 1893 (Part – 1): 2016. The grade of concrete used in this study is M20. The permissible stresses in concrete as per IS 456:2000 is 8920 kN/m2 (0.446fck).

The base shear acquired by pushover analysis of Underground Rectangular Water tank with 72 cum capacity in X-direction is 4235.556 kN at yield point and 954.689 kN at performance point. The base shear acquired by pushover analysis of Underground Rectangular Water tank with 72 cum capacity in Y-direction is 4853.874 kN at yield point and 1175.704 kN at performance point.

Displacement acquired by pushover analysis of Underground Rectangular Water tank with 72 cum capacity in X-direction is 0.0014 m and 0.0003 m at yield and performance point respectively. Displacement acquired by pushover analysis of Underground Rectangular Water tank with 72 cum capacity in Y-direction is 0.0031 m and 0.0008 m at yield and performance point respectively.

The observed maximum horizontal displacement of the Underground Rectangular water tank having a capacity of 72 cum due to lateral forces by Nonlinear static analysis is 0.0245 m in X-direction, which is within the permissible limit. The maximum horizontal displacement of the Underground Rectangular water tank having a capacity of 72 cum due to lateral forces by Nonlinear static analysis is 0.0517 m in Y-direction, which is within the permissible limit.

The maximum membrane stress in the top slab, long wall, short wall & base slab of an Underground water tank with 72 cum capacity are 3358.511 kN/m2, and 17406.769 kN/m2, 18292.256 kN/m2 & 11050.95 kN/m2 respectively.

The guidelines and specifications for Pushover analysis and design of Underground Rectangular Water tank structures are not available in Indian standard codes. An attempt has been made to predict the seismic response of Underground Rectangular Water tank structures by Non-linear Static Analysis procedures.

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