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Optimization of Staging Height of RCC Overhead Water Tank in High Seismic Zones Using P-Delta Analysis

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Abstract: This study investigates the P-delta effect, which is a secondary effect or a geometric non-linear effect in the analysis of a circular overhead water tank with a capacity of 100 KL using STAAD software in high seismic zones, i.e., Zone IV & Zone V with a focus on optimization of staging height and to quantify the effect of P-Delta. Initially, a linear static analysis was performed without considering the P-Delta effect to determine the shear forces, bending moments and lateral displacements due to all possible loads including seismic and wind loads acting on RCC overhead water tanks. Subsequently, the P-Delta effect has been considered to assess the structural behaviour of the RCC overhead water tank with varying staging heights. To optimize the staging height, the maximum lateral displacement has been considered as the governing criteria. Based on the analysis, the optimum staging heights can be observed at 30 m. and 33 m. in Seismic Zone V and Zone IV respectively.
Keywords: P-Delta effect, Optimization, Staging Height, Over Head Water Tank, Seismic Analysis

I. INTRODUCTION

Rapid urban growth and population growth requires the development of a reliable water supply, especially in earthquake-prone regions where the risk of damage from earthquakes is high. An important part of this system is reinforced concrete (RCC) waterworks, which must be designed to withstand seismic forces while ensuring proper water distribution. The water distribution area will increase as the above water tank's staging height rises.

The P-Delta effect plays a crucial role in the analysis of structures when they encounter with lateral forces. When a tall structure or structural component is subjected to lateral forces or significant lateral displacement, it leads to additional moments, and/or axial force distribution at the base of the structure. In the P-Delta analysis initially structural response under the imposed loads, conduct a linear static analysis without considering the P-Delta effect, later that The P-Delta effect is to be taken into account in this analysis either geometric nonlinear analysis or iterative process or both.

In this study to assess and quantify the structural performance parameters like axial force, shear force, bending moment of the overhead water tank with and without P-Delta effect in accordance with IS codal provisions, subsequently to optimize the staging height of the 100 KL circular RCC overhead water tank in high seismic zones.

II. NUMERICAL MODELLING

A circular flat bottom RC overhead water tank has modelled in Bentley Staad pro software. The columns, brace/tie beams and ring beams are considered as beam elements and tank walls, top and bottom slabs are considered as plate elements with the following input parameters

Table I - Input Parameters for tank Model

S No.	Parameter	Value
1	Tank Type	Flat bottom circular RCC Overhead tank
2	Capacity of tank	100 KL
3	Dia. of Tank	6.5 m
4	Height of tank	3.5 m
5.	Free board	0.3 m
6	Dead storage	0.2 m
7	No. of columns	6 No.s

8	Centre to centre Spacing between Bracing/Tie Beams	3.0 m
9	Columns with fixed supports at base	450 X 450 mm
10	Clear cover	for columns 40mm & for beams 30 mm
11	Thickness of tank roof	150 mm
12	Thickness of tank side walls and bottom floor slab	250 mm
13	Walk way around the tank	1m. Wide and 125 mm thick
14	Ring beam	300 X 600 mm
15	Tie beam/ Brace beam	400 X 450 mm
16	Grade of Concrete	M 30
17	Grade of Steel	Fe 415
18	Staging Height	From 9 m onwards

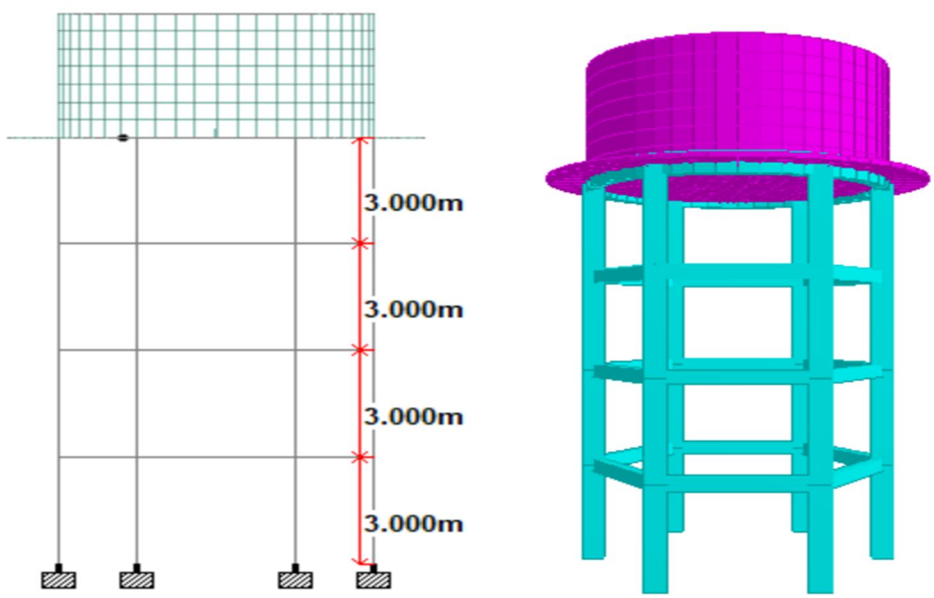

Fig 1. Model of a Circular Flat Bottom Overhead Tank

III. LOAD CONSIDERATIONS

The following loads are considered for the analysis of the overhead water tank

1) *Dead Load:* Self-weight of the all-structural elements.
2) *Live Load*: 2 KN/m^2 on the roof for maintenance.
3) *Seismic Loads:* In High seismic zones (IV & V), the overhead circular water tank was first given the seismic load; in accordance with IS 1893-2016, the appropriate zone factors are 0.24 & 0.36 respectively and the importance factor is 1.5. considering that the structure has a Special Moment Resisting Frame (SMRF) and is to be erected on Type I (Hard) soil, 5.0 was chosen as the reduction factor with a damping ratio of 5 %. The seismic load was applied in all four directions (+X, -X, +Z, and -Z) using these values.

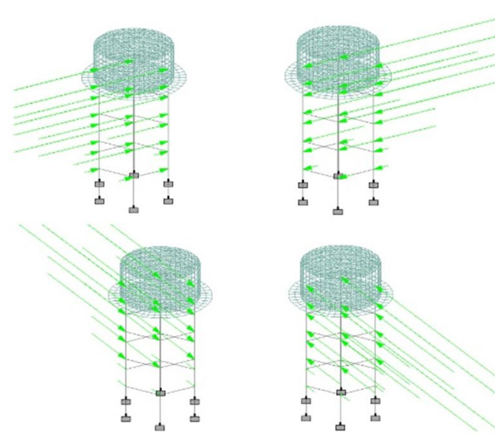

Fig 2. Seismic Loading on a tank

4) Wind Loads:

As per IS 875 Part III; The Basic Wind Speed (V_b) 50 m/sec for Bhuj & 47 m/sec for Ambala, Risk Coefficient k_1, Topography factor k_3, importance factor cyclonic region k_4 are taken as 1 and Terrain, Height and structure factor k_2 (Terrain I)

Design wind speed $V_Z = V_b.k_1.k_2.k_3.k_4$

Design wind pressure at Z height $P_Z = 0.6\ Vz^2$

Design wind pressure $P_d = K_d \text{ X } K_a \text{ X } K_c \text{ X } P_z$

wind directionality factor $K_d = 1$

Area averaging factor $K_a = 0.9$ &

Combination factor $K_c = 0.9$

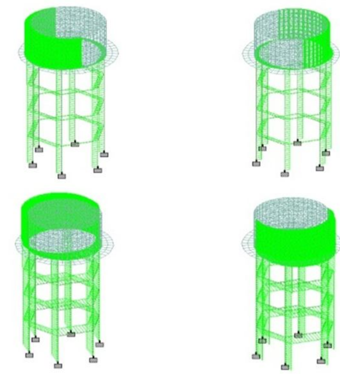

Fig 3. Wind loads acting on a tank

5) Water pressure on tank walls:

The circumstances were taken into account when analyzing the tank structure in both full and empty states.

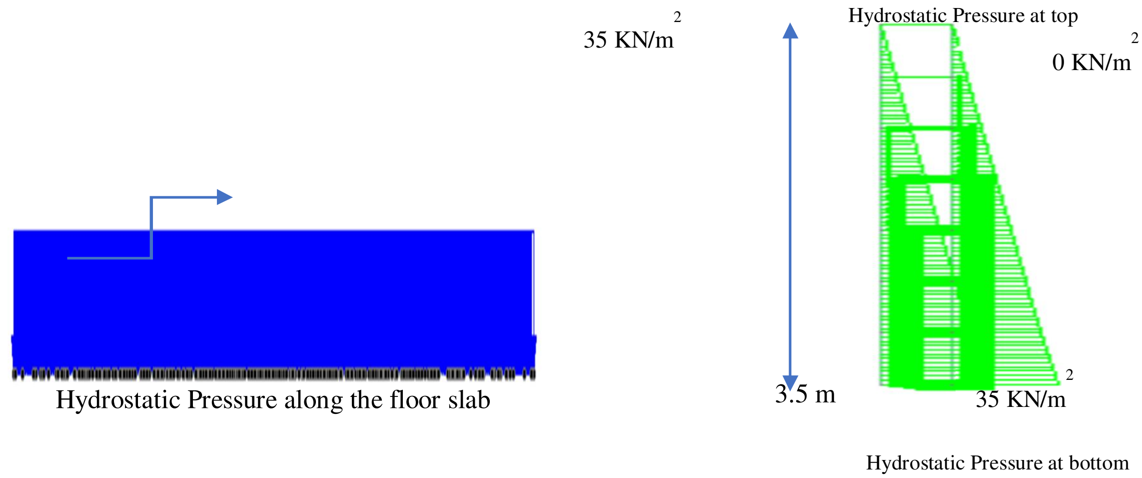

Fig 4 Hydrostatic Pressure on tank walls and floor slab under tank full condition

6) Load combinations:

The Load combinations are taken from IS 456:2000 & IS 875-Part V

1.5 (DL+LL)

- *Earthquake Load Combinations*

1.5 (DL+WATER LOAD ± EQ Load)
0.9(DL+WATER LOAD) ±1.5 EQ Load
1.2 (DL+LL+WATER LOAD ± EQ Load)
1.0 (DL+WATER LOAD ± EQ Load)
1.0 (DL+LL+WATER LOAD ± EQ Load)

- *Wind Load Combinations*

1.5 (DL+WATER LOAD ±WIND Load)
0.9(DL+WATER LOAD) ± 1.5 WIND Load
1.2 (DL+LL+WATER LOAD ±WIND Load)
1.0 (DL+WATER LOAD±WIND Load)
1.0 (DL+LL+WATER LOAD±WIND Load)

IV. RESULTS AND DISCUSSIONS

A 100 KL circular overhead water tank has been created and analysed in Staad Pro with tank empty and full conditions and drawn the following results with and without the P-Delta effect in high seismic zones.

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As a result, the maximum lateral displacement in Seismic Zone V exceeding the allowable limit at a staging height of 33 meters, Therefore, the structural performance parameters are analysed and compared and quantified the P-Delta effect from a staging height of 27m in Zone V & IV.

A. *Axial Force (Fx):*

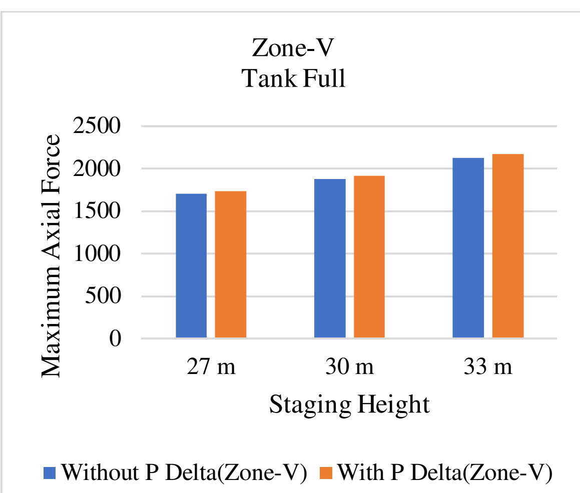
From the analysis the maximum axial force is developed at the base of the structure with a critical load combination of 1.5 (DL+WATER LOAD+WIND ±X) in tank full condition and 1.5(DL+WIND±X) in empty condition. The maximum axial force increases with staging height and shifts from seismic zone IV to zone V, as the following table makes evident.

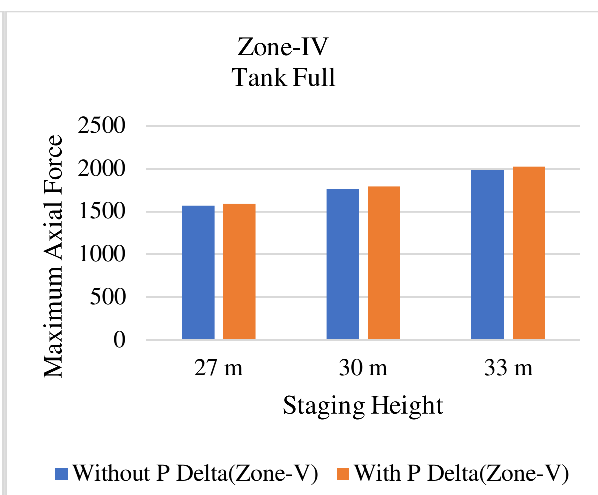
Table II - Maximum axial force (Fx) in tank full condition

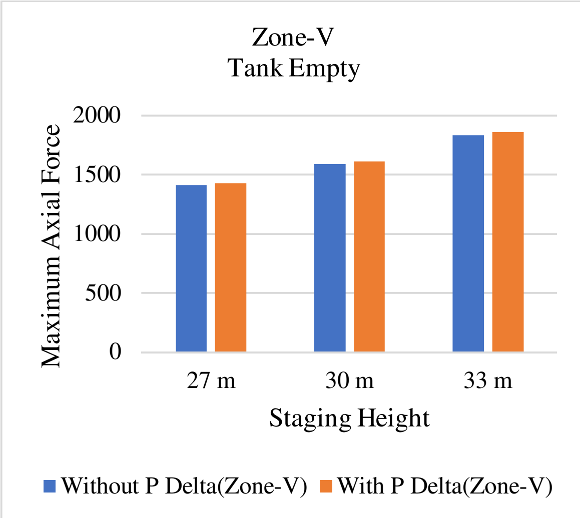
STAGING HEIGHT (m)	TANK FULL					
	MAXIMUM AXIAL FORCE (KN)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	1703.38	1731.042	1.60	1567.282	1590.46	1.46
30	1879.925	1914.893	1.83	1758.016	1788.545	1.71
33	2124.103	2168.335	2.04	1987.637	2026.697	1.93

Table III - Maximum axial force (Fx) in tank empty condition

STAGING HEIGHT (m)	TANK EMPTY					
	MAXIMUM AXIAL FORCE (KN)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	1413.854	1429.775	1.11	1277.756	1291.36	1.05
30	1590.399	1610.912	1.27	1468.399	1486.637	1.23
33	1834.59	1861.952	1.47	1698.123	1722.854	1.44







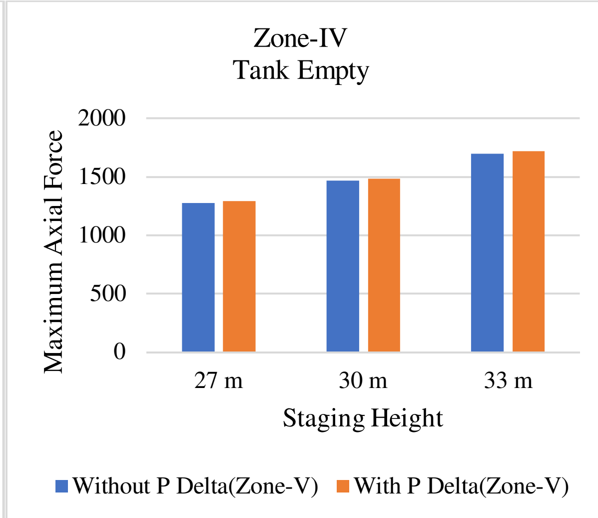


Fig 5. Maximum axial force in tank full and empty condition (Zone V & IV)

In Figure 5, the maximum axial force for a certain staging height for a given zone is shown to have an average increment of **1.8%** in tank full condition and **1.3%** in tank empty condition which takes the P-Delta effect into account.

B. *Maximum Shear Force (Fy):*

From the analysis the maximum Shear force increases with staging height and shifts from seismic zone IV to zone V, as the following table makes evident. The maximum shear force developed at 30 m & 33 m staging height under a critical load combination of 1.5 (DL+WATER LOAD+ WIND ±X).

Table IV - Maximum Shear force (Fy) in tank full condition

STAGING HEIGHT (m)	TANK FULL					
	MAXIMUM SHEAR FORCE (KN)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	159.537	161.091	0.965	138.204	139.242	0.75
30	161.723	167.095	3.215	142.885	147.587	3.19
33	179.356	185.511	3.318	159.453	164.885	3.29

Table V - Maximum Shear force (Fy) in tank Empty condition

STAGING HEIGHT (m)	TANK EMPTY					
	MAXIMUM SHEAR FORCE (KN)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	150.321	153.192	1.87	129.243	131.726	1.88
30	161.722	165.115	2.05	142.868	145.905	2.08
33	179.356	183.48	2.25	159.453	163.182	2.29

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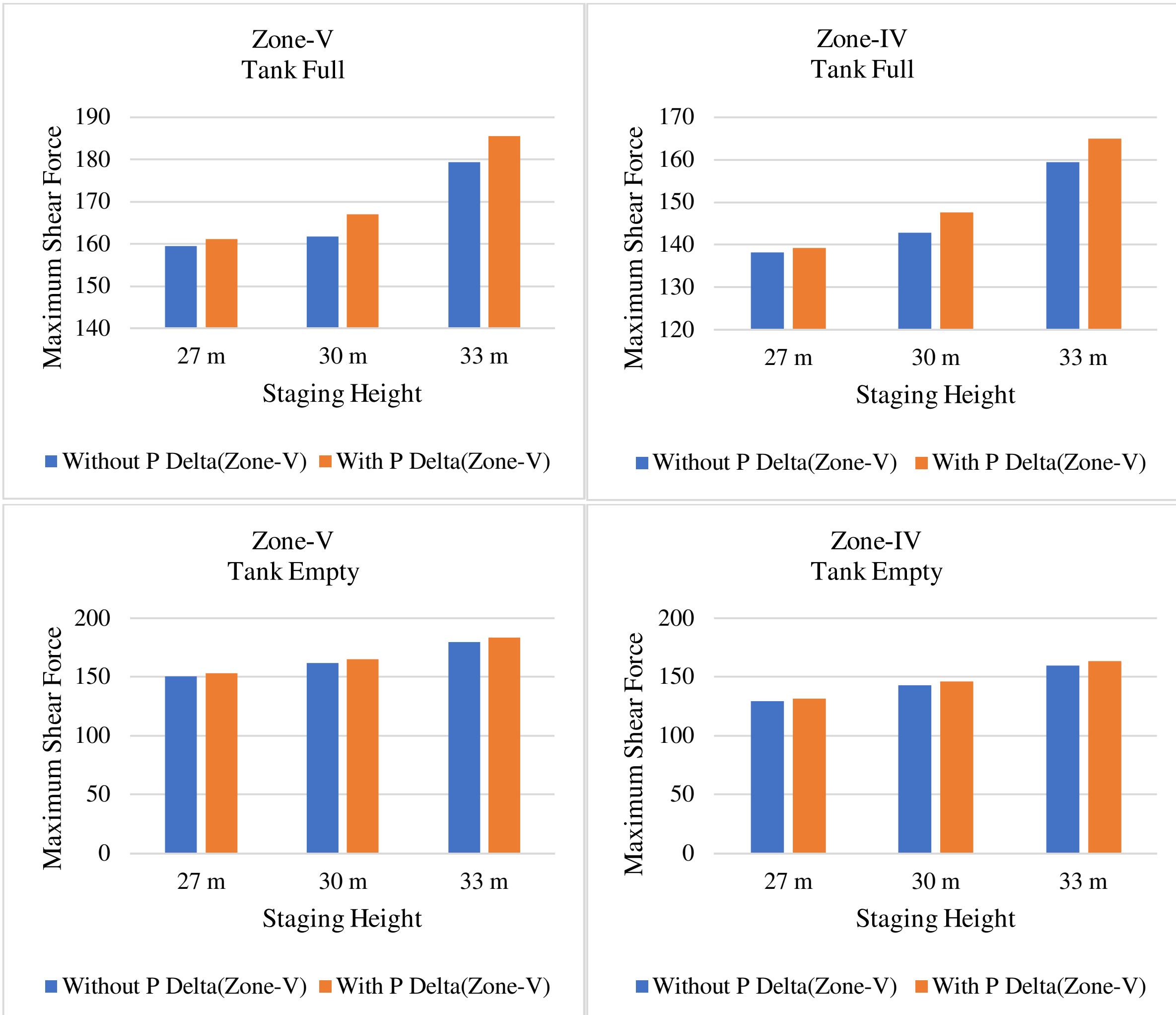

Fig 6. Maximum Shear force in tank full and empty condition (Zone V & IV)

In Figure 6, the maximum shear force for a certain staging height for a given zone is shown to have an average increment of 2.5% in tank full condition and 2.05% in tank empty condition which takes the P-Delta effect into account

C. Maximum Bending Moment:

From the analysis the maximum bending moment increases with staging height and shifts from seismic zone IV to zone V, as the following table makes evident. The maximum bending moment developed under a critical load combination of 1.5 (DL+WATER LOAD+ WIND ±X).

Table VI - Maximum Bending Moment - tank full condition

STAGING HEIGHT (m)	TANK FULL					
	MAXIMUM BENDING MOMENT (KN-m)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	232.711	240.273	3.15	198.46	204.873	3.13
30	251.237	259.932	3.35	220.625	228.24	3.34
33	279.891	289.849	3.44	247.549	256.341	3.43

Table VII - Maximum Bending Moment - tank empty condition

STAGING HEIGHT (m)	TANK EMPTY					
	MAXIMUM BENDING MOMENT (KN-m)					
	ZONE V			ZONE IV		
	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE	WITHOUT P DELTA	WITH P DELTA	% OF DIFFERENCE
27	232.71	237.349	1.95	198.458	202.474	1.98
30	251.236	256.717	2.14	220.599	225.507	2.18
33	279.891	286.547	2.32	247.55	253.572	2.37

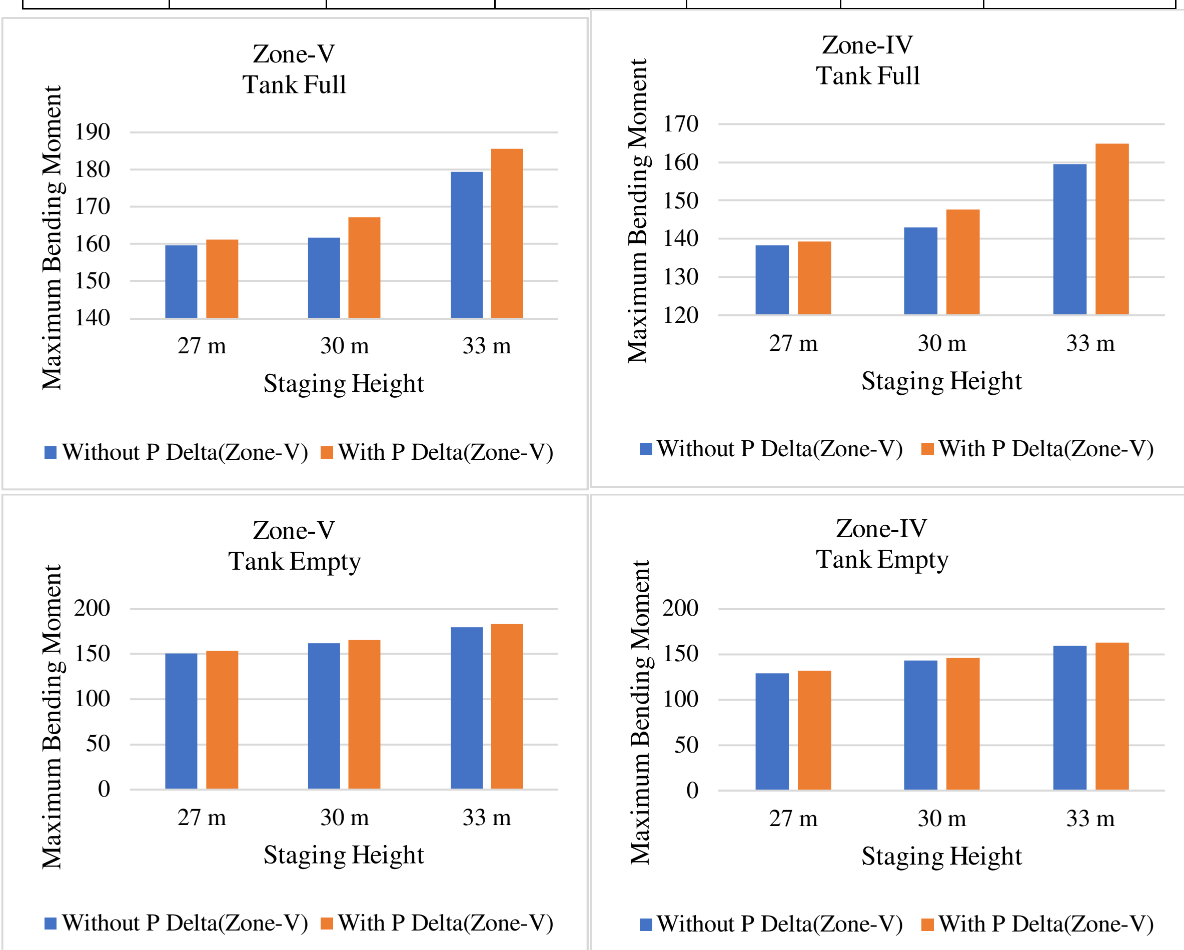

Fig 7. Maximum Bending Moment in tank full and empty condition (Zone V & IV)

In Figure 7, the maximum Bending Moment for a certain staging height for a given zone is shown to have an average increment of **3.3%** in tank full condition and **2.15%** in tank empty condition which takes the P-Delta effect into account

D. Base Shear:

The base shear value depends on the seismic weight of the structure, zone factor, Importance factor, Response reduction factor and natural time period. In zone V gets the maximum base shear values when compares with the Zone IV at common staging height. The variation of base shear values considering the P-Delta effect is shown below

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Table VIII - Maximum Bending Moment - tank full condition

STAGING HEIGHT (m)	TANK FULL					
	BASE SHEAR (KN)					
	TANK FULL			TANK EMPTY		
	ZONE V	ZONE IV	% OF DIFFERENCE	ZONE V	ZONE IV	% OF DIFFERENCE
27	188.52	122.95	34.78	129.78	86.45	33.54
30	184.43	120.74	34.53	129.68	86.52	33.28
33	181.11	118.93	34.33	129.77	86.67	33.21

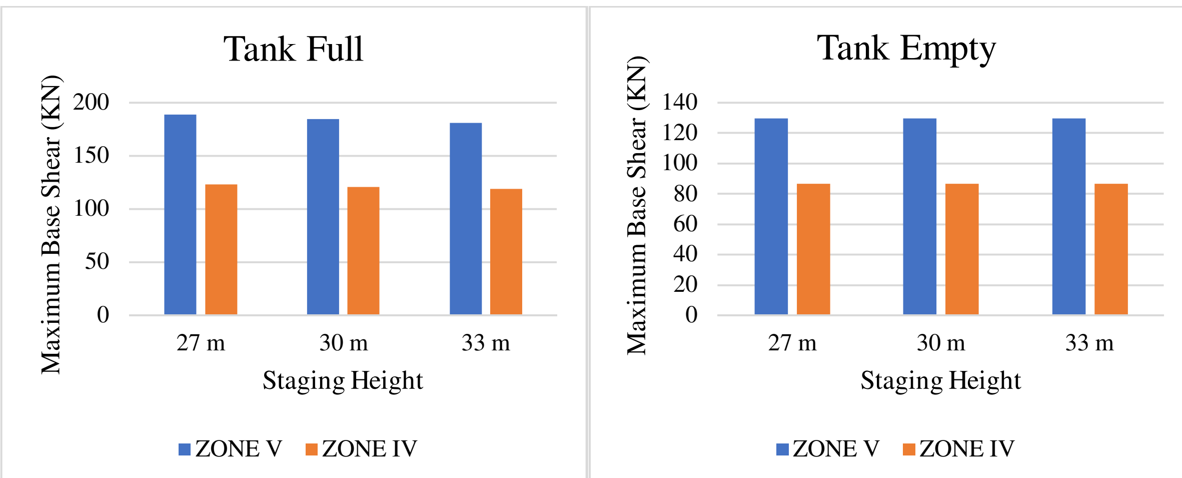

Fig 7. Maximum Base Shear in tank full and empty condition in both Zone V & IV

E. Quantity of concrete & Reinforcement in the staging without considering the tank walls:

1) Quantity of Concrete

The amount of concrete needed for the staging of an overhead water tank is displayed in the following table at different staging heights without taking the tank walls into account. It is noted that the amount of concrete remains the same at common staging heights regardless of whether the P-Delta effect is taken into account or not.

Table IX - Quantity of concrete at varying staging heights

STAGING HEIGHT (m)	9	12	15	18	21	24	27	30
Quantity of Concrete (m^3)	21.6	28.8	35.9	43.1	50.2	57.4	64.6	71.7

The Total Quantity of Reinforcement in the staging in KN

The amount of reinforcement needed for the staging of an overhead water tank is displayed in the following table at different staging heights without taking the tank walls into account. It is observed that, whether the P Delta effect is taken into account, the amount of reinforcement is increasing at common staging height.

Table X - Quantity of Reinforcement at varying staging heights in Zone V

STAGING HEIGHT (m)	9	12	15	18	21	24	27	30
WITHOUT	17.736	22.502	26.727	30.941	38.164	45.708	55.799	63.865

P DELTA								
WITH P DELTA	19.832	24.707	29.8	35.755	41.641	49.37	60.619	67.867

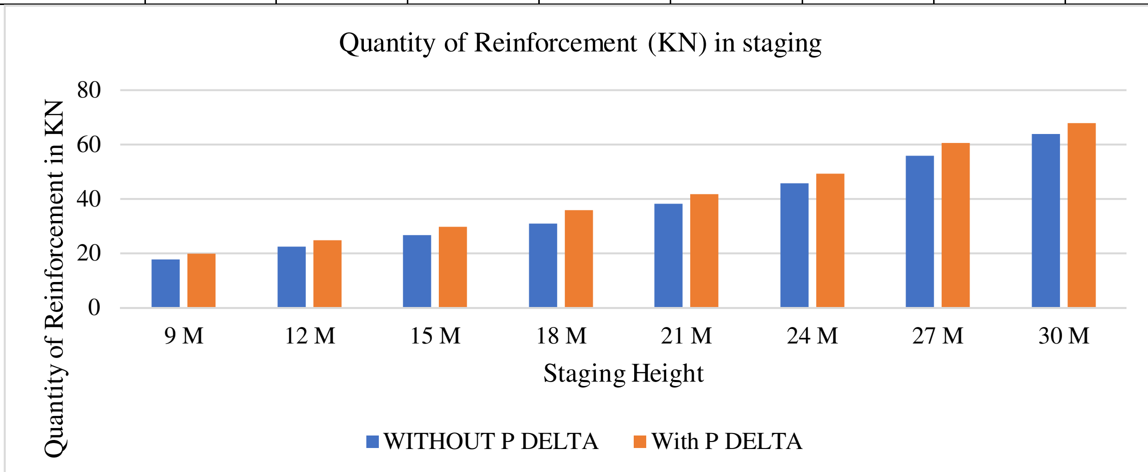

Fig 10. Quantity of Reinforcement in the staging in Zone V at different staging heights

F. Maximum lateral displacement:

The permissible maximum lateral displacement is considered from clause 20.5 of IS 456-2000 (the lateral sway at the top should not exceed H/500) [1].

In P Delta analysis the maximum permissible displacement (Hs/500) is considered from "C4.13.5- P-Delta effect: of IITK-GSDMA Guidelines for Seismic Design of Liquid storage tanks" [9]

Table XI - Maximum lateral displacement at top in Zone V – Tank full condition

STAGING HEIGHT (m)	TANK FULL (ZONE V)				
	MAXIMUM LATERAL DISPLACEMENT AT TOP				
	CRITICAL LOAD COMBINATION	WITHOUT P DELTA (mm)	WITH P DELTA (mm)	PERMISSIBLE DISPLACEMENT (Hs/500)	% OF DIFFERENCE
9	1.0 (DL+LL+WATER LOAD+ EQ +X)	11.311	11.455	18 mm	1.26
12	1.0 (DL+LL+WATER LOAD+ EQ +X)	15.447	15.633	24 mm	1.19
15	1.0 (DL+LL+WATER LOAD+ EQ +X)	19.559	19.866	30 mm	1.55
18	1.0 (DL+LL+WATER LOAD+ EQ +X)	23.812	24.223	36 mm	1.70
21	1.0 (DL+LL+WATER LOAD+ EQ +X)	28.319	28.842	42 mm	1.81
24	1.0 (DL+LL+WATER LOAD+WIND +X)	33.253	33.947	48 mm	2.04
27	1.0 (DL+LL+WATER LOAD+WIND +X)	45.892	46.932	54 mm	2.22
30	1.0 (DL+LL+WATER LOAD+WIND +X)	55.776	57.151	60 mm	2.41
33	1.0 (DL+LL+WATER LOAD+WIND +X)	70.556	72.399	66 mm	2.55

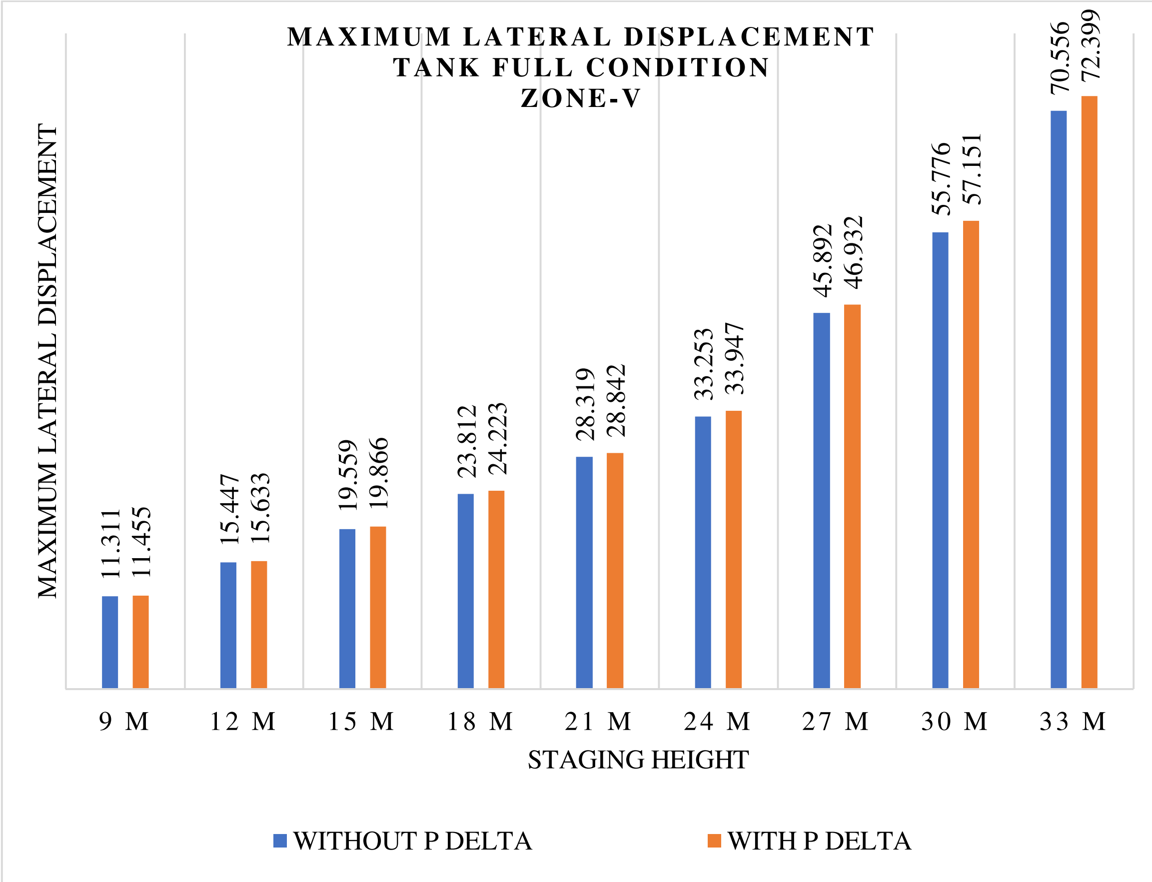

Fig 11. The maximum lateral displacement (mm) at top in Zone V at different staging heights

From Table XI The earthquake load is the predominant force up to 21 meters of staging height; after that, the wind load is the predominant for determining the maximum lateral displacement and it is clearly observed that the P-Delta effect has a greater impact as the staging height increases

Table XII - Maximum lateral displacement at top in Zone V – Tank empty condition

STAGING HEIGHT (m)	TANK EMPTY (ZONE V)				
	MAXIMUM LATERAL DISPLACEMENT AT TOP				
	CRITICAL LOAD COMBINATION	WITHOUT P DELTA (mm)	WITH P DELTA (mm)	PERMISSIBLE DISPLACEMENT (Hs/500)	% OF DIFFERENCE
9	1.0 (DL+LL+ EQ+X)	6.28	6.317	18 mm	0.59
12	1.0 (DL+LL+ EQ+X)	8.965	9.029	24 mm	0.71
15	1.0 (DL+LL+ EQ+X)	11.78	11.876	30 mm	0.81
18	1.0 (DL+LL+ WIND+X)	17.23	17.397	36 mm	0.96
21	1.0 (DL+LL+WIND +X)	24.262	24.523	42 mm	1.06
24	1.0 (DL+LL+WIND +X)	33.254	33.652	48 mm	1.18
27	1.0 (DL+LL+WIND +X)	45.892	46.5	54 mm	1.31
30	1.0 (DL+LL+WIND +X)	55.777	56.594	60 mm	1.44
33	1.0 (DL+LL+WIND +X)	70.557	71.697	66 mm	1.59

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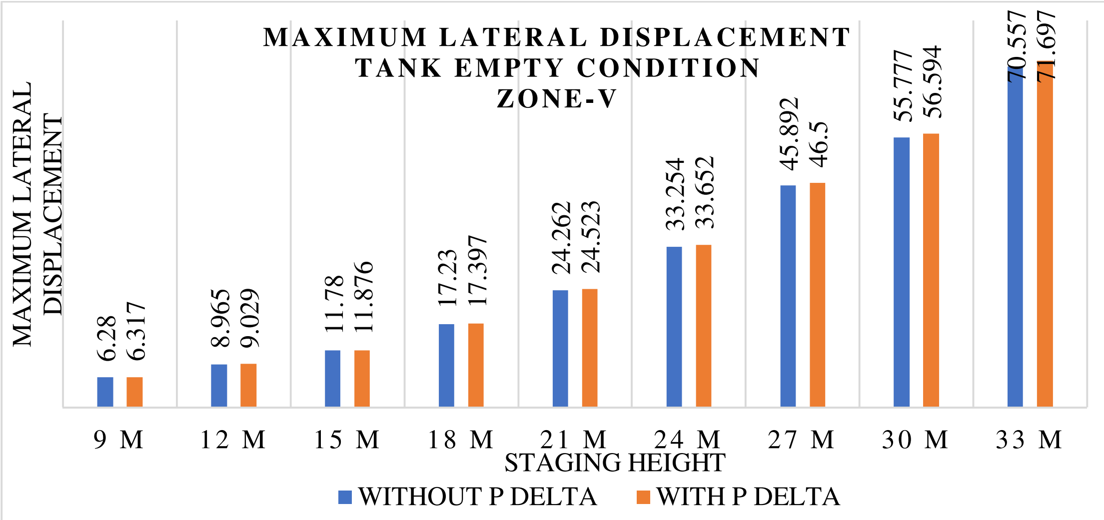

Fig 12. The maximum lateral displacement (mm) at top in Zone V at different staging heights

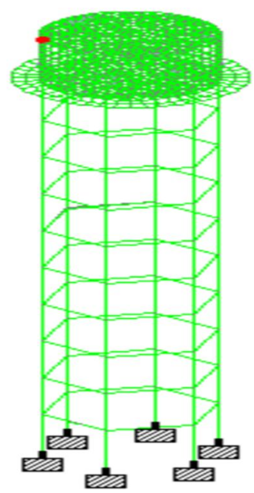

Fig 13. The maximum lateral displacement showing at top of the overhead water tank

Table XIII - Maximum lateral displacement at top in Zone IV – Tank full condition

STAGING HEIGHT (m)	TANK FULL (ZONE IV)				
	MAXIMUM LATERAL DISPLACEMENT AT TOP				
	CRITICAL LOAD COMBINATION	WITHOUT P DELTA (mm)	WITH P DELTA (mm)	PERMISSIBLE DISPLACEMENT (Hs/500)	% OF DIFFERENCE
27	1.0 (DL+LL+WATER LOAD+WIND +X)	38.446	39.318	54 mm	2.22
30	1.0 (DL+LL+WATER LOAD+WIND +X)	48.728	49.93	60 mm	2.41
33	1.0 (DL+LL+WATER LOAD+WIND +X)	62.331	63.959	66 mm	2.55
36	1.0 (DL+LL+WATER LOAD+WIND +X)	77.832	80.1	72 mm	2.83

Table XIV - Maximum lateral displacement at top in Zone IV – Tank empty condition

STAGING HEIGHT (m)	TANK EMPTY (ZONE IV)				
	MAXIMUM LATERAL DISPLACEMENT AT TOP				
	CRITICAL LOAD COMBINATION	WITHOUT P DELTA (mm)	WITH P DELTA (mm)	PERMISSIBLE DISPLACEMENT (Hs/500)	% OF DIFFERENCE
27	1.0 (DL+LL+WIND +X)	38.447	38.963	54 mm	1.32
30	1.0 (DL+LL+WIND +X)	48.729	49.454	60 mm	1.47
33	1.0 (DL+LL+WIND +X)	62.332	63.356	66 mm	1.62
36	1.0 (DL+LL+WIND +X)	77.833	79.242	72 mm	1.78

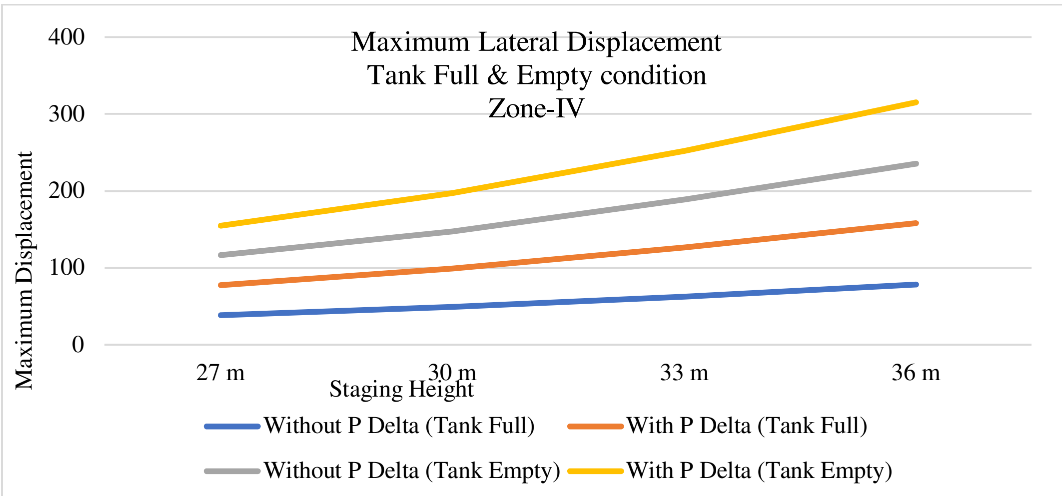

Fig 14. The maximum lateral displacement in Zone IV

From table XI & table XII, the maximum lateral displacement exceeds the permissible displacement at a staging height of 33 m in Zone V both tank full and empty conditions. Subsequently, From table XIII & table XIV, the maximum lateral displacement exceeds the permissible displacement at a staging height of 36 m in Zone IV both tank full and empty conditions.

V. DISCUSSIONS

1) The P Delta effect has a greater impact from the corresponding parameters, such as displacements, axial shear, shear force, and bending moment, as the staging height increases.
2) The earthquake load is the predominant force up to 21 meters of staging height; after that, the wind load is the predominant for determining the maximum lateral displacement.
3) Moving from Seismic Zone IV to Seismic Zone V for a common staging height result in increases in displacement, shear force, and bending moments.
4) As a result, the maximum lateral displacement in Seismic Zone V exceeding the allowable limit at a staging height of 33 meters, hence the analysis in Zone IV is performed from a staging height of 27 meters.

VI. CONCLUSION

The following conclusions have been shown after the analysis of a circular overhead water tank in high seismic zones i.e., Zone IV & V with the aforementioned parametric study as outlined below:

1) The maximum axial force for a certain staging height for a given zone is shown to have an average increment of 1.8% in tank full condition and 1.3% in tank empty condition which takes the P-Delta effect into account.

2) The maximum shear force for a certain staging height for a given zone is shown to have an average increment of 2.5% in tank full condition and 2.05% in tank empty condition which takes the P-Delta effect into account.
3) The maximum Bending Moment for a certain staging height for a given zone is shown to have an average increment of 3.3% in tank full condition and 2.15% in tank empty condition which takes the P-Delta effect into account.
4) The optimum staging height of 30m. has been arrived in seismic zone V by considering the exceedance of maximum lateral displacement i.e., Hs/500 for the cases with & without P-Delta and tank full & empty conditions.
5) The optimum staging height of 33m. has been arrived in seismic zone IV by considering the exceedance of maximum lateral displacement i.e., Hs/500 for the cases with & without P-Delta and tank full & empty conditions.

VII. FUTURE SCOPE

The current investigations can be extended by considering the following parameters
1) The tank's storage capacity can be increased in various soil conditions, more research can be done.
2) In this study, only simple bracing was performed; additionally, because the type of bracing varies, the outcomes may also vary.
3) Since the current study focused on seismic zones IV and V, additional seismic zones might be taken into consideration as well, which could lead to more generalised outcomes.

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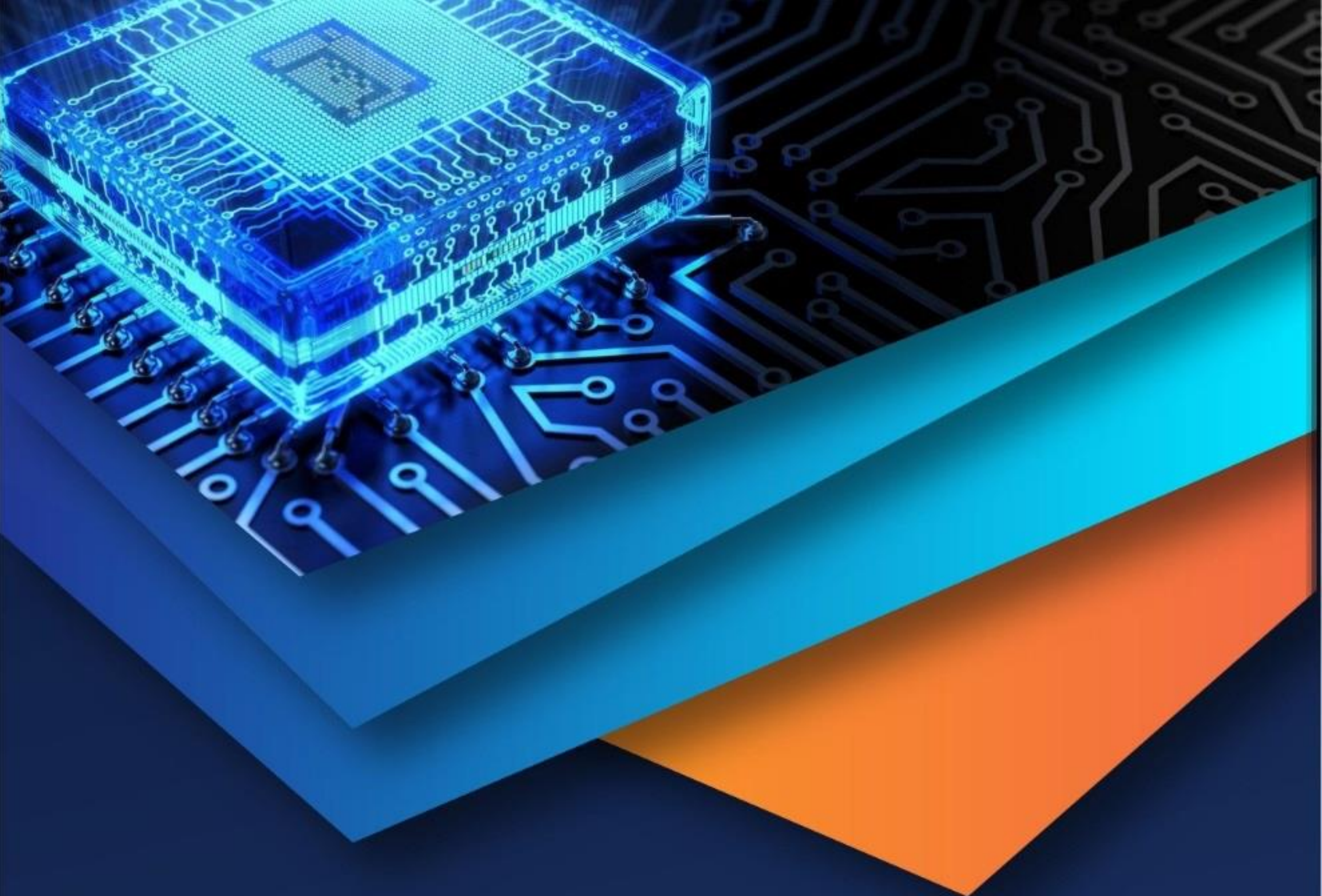

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