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Comparative Analysis and Design of Bridge Pier for various Geometries along height

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Abstract: Slender member is subjected to axial load and biaxial bending moment and fails due to buckling. This buckling is caused due to slenderness effect also known as 'P∆' effect. This buckling gives rise to excessive bending moment occurring at a point of maximum deflection. This additional bending moment is considered in second order analysis. The objective of the research reported in this paper is to formulate bending moment equation by using beam column theory and to study the behaviour of solid circular section and hollow circular section of bridge pier. The optimization in area of cross section is done by providing a combination of solid and hollow circular section in place of a solid circular section of pier within permissible limits. A comparative study on behaviour for all three conditions is been carried out.
Keywords: slender column, buckling, 'P∆' effect, beam-column, second order analysis, bridge pier.

I. INTRODUCTION

Piers are not only subjected to axial load but also forces in longitudinal direction as well as in transverse direction. These forces cause moment in longitudinal direction and transverse direction at base of pier. Thus, pier is idealized as a column subjected to axial load and biaxial moment. These forces cause the pier to buckle along its height. The moment due to buckling is not considered in first order analysis.

In order to get accurate forces one has to go for second order analysis where in the buckling effect is considered. Beam column theory is one of the methods to calculate the bending moment by second order analysis.

Iterative neutral axis method is used to design the cross section of pier. In a section subjected to axial load combined with two orthogonal moments, by assuming the neutral axis at certain depth and stress at that point is to be calculated. This stress at neutral axis should be zero or else the procedure is revised for another trail.

II. SECOND ORDER ANALYSIS USING BEAM-COLUMN THEORY

Beams subjected to axial compression with lateral loads act as beam-column. The basic equation for analysis of beam-column can be derived by considering a beam as shown in Figure1.

The beam is subjected to an axial compressive force ***P*** and lateral load of intensity '***q'*** which varies with the distance '***x***' along the beam.

Consider an element of length 'dx' between two cross sections taken normal to the original axis of beam as shown in Figure 2.

The lateral load has a constant intensity 'q' over a distance 'dx' and will be assumed positive when in direction of positive y axis which is downward in this case.

The shearing force V and bending moment M acting on either side of the elements are assumed positive in the downward direction.

The relation between load, shear force and bending moment are obtained from the equilibrium of the element in Figure 2. On summing forces in the y direction it gives.

$$-V+qdx+(V+dv)=0$$

$$q=-\frac{dV}{dx} \qquad (1)$$

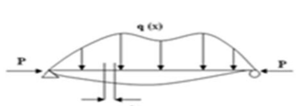

Figure1. General loading beam-column analysis

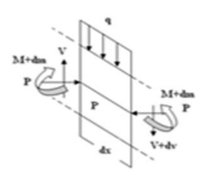

Figure2. Cross section of beam

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Taking the moment about point on beam and assuming that angle between the axis of beam and horizontal axis is small, we obtain,

$$M + q\,dx\,\frac{dx}{2} + (V + dv) - (M + dM) + P\,\frac{dy}{dx}\,dx = 0$$

If terms of second-degree are neglected, this equation becomes

$$V = \frac{dM}{dx} - P\,\frac{dy}{dx} \qquad (2)$$

If the effects of shearing deformations and shortening of the beam axis are neglected the expression for the curvature of the axis of the beam is,

$$EI\,\frac{d^2y}{dx^2} = -M \qquad (3)$$

The quantity EI represents the flexural rigidity of beam in a plane of bending, i.e. XY plane, which is assumed to be plane of symmetry. Combining equation (3) with equation (1) and equation (2) we can express the differential equations of the axis of the beam in the following alternate forms:

$$EI\,\frac{dy}{dx} + P\,\frac{dy}{dx} = -V \qquad (4)$$

$$EI\,\frac{dy}{dx} + P\,\frac{dy}{dx} = q \qquad (5)$$

Equations (1) to (5) are the basic differential equations for bending of beam-column. If the axial force's P equals zero, these equations reduces to the usual equations for bending by lateral loads only. The nature of the axial forces have significant effect on the deflections and ultimately on the secondary moments.

III. ITERATIVE NEUTRAL AXIS METHOD

Iterative neutral axis method is used for design of slender member which are subjected to axial load and biaxial moment. In this method, some percentage of steel is assumed and the moment of inertia of full section is calculated. Then inclination of neutral axis is calculated. Then, moment of inertia and eccentricity of cracked section is computed. Compute stress at neutral axis, if it is zero, and if stresses at extreme fibers are within permissible limit, the assumed percentage of steel is acceptable otherwise the neutral axis has to be shifted and same procedure has to be carried out.

IV. THEOROTICAL FORMULATION

A. Trapezoidal Load Throughout the Height of Pier

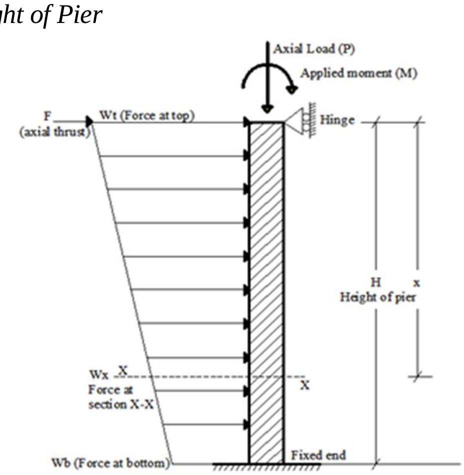

Figure 3 Trapezoidal force acting on complete height of pier

$$W_x = W_T - \left[\frac{\left(W_T - W_B\right)x}{H}\right] \qquad (5)$$

1) First Order Analysis Of Pier

Let 'M_x' be the bending moment at a general section '*XX*' at a distance 'x' from top of pier,

$$\therefore M_x = -M - Fx + R_T - \frac{W_T x^2}{2} + \frac{(W_T - W_B)x^3}{6H} \qquad (7)$$

$$R_T = \frac{3M}{2H} + F + \frac{11W_T H}{40} + \frac{W_B H}{10}$$

$$M_x = -M + \frac{3M}{2H}x + \frac{11W_T H}{40}x + \frac{W_B H}{10} - \frac{W_T x^2}{2} + \frac{(W_T - W_B)x^3}{6H} \qquad (8)$$

2) Second Order Analysis Of Pier

Considering the same values used in first order analysis as given above:

Substituting constant k_w in equation (6)

$$k_w = \frac{\left(W_T - W_B\right)}{H}$$

$$W_x = W_T - k_w x$$

Bending moment at a general section 'x' is given by

$$M_x = Py - M_A + (R_T - F)x - \frac{W_T x^2}{2} + \frac{k_w x^3}{6} \qquad (9)$$

$$y = complementary\ \ solution + particular$$

$$y_c = A\sin(\alpha x) + B\cos(\alpha x)$$

$$\backslash y_p = -\frac{k_w}{6P}x^3 + \frac{W_T}{2P}x^2 + \frac{x}{P}\left[F - R_T + \frac{k_w}{\alpha^2}\right] + \frac{1}{P}\left[M_A - \frac{W_T}{\alpha^2}\right]$$

Complete solution,

$$y = A\sin(\alpha x) + B\cos(\alpha x) - \frac{k_w}{6P}x^3 + \frac{W_T}{2P}x^2 + \frac{x}{P}\left[F - R_T + \frac{k_w}{\alpha^2}\right] + \frac{1}{P}\left[M_A - \frac{W_T}{\alpha^2}\right] \qquad (10)$$

On substituting the boundary condition, $x=0, y=0$

In equation (10) we get,

$$B = -\frac{1}{P}\left[M_A - \frac{W_T}{\alpha^2}\right]$$

On substituting boundary condition, $x=H, y=0$ and $x=H \; \frac{\partial y}{\partial x} = 0$

In equation (10) we get,

$$A = \frac{1}{\sin(\alpha H)}\left[\frac{k_w}{6P}H^3 - B\cos(\alpha H) - \frac{W_T}{2P}H^2 - \frac{H}{P}\left[F - R_T + \frac{k_w}{\alpha^2}\right] - \frac{1}{P}\left[M_A - \frac{W_T}{\alpha^2}\right]\right] \tag{11}$$

On substituting the values of constants in the deflection equation (10)

$$R_T = \frac{1}{\frac{1}{P}\left[\frac{\tan(\alpha H)}{\alpha} - H\right]} \times \left[\frac{W_T}{P}H\left\{\frac{\tan(\alpha H)}{\alpha} - \frac{H}{2}\right\} - B\left\{\sin(\alpha H)\tan(\alpha H) + \cos(\alpha H)\right\} - \frac{k_w H}{P\alpha}\left\{\frac{H\tan(\alpha H)}{2} + \frac{1}{\alpha}\right\} + \frac{\tan(\alpha H)}{\alpha P}\left\{F + \frac{k_w}{\alpha^2}\right\} + \frac{k_w}{6P}H^3 + \frac{W_T}{P\alpha^2} - \frac{HF}{P} - \frac{M}{P}\right] \tag{12}$$

B. Validation for the Bending Moment Equation

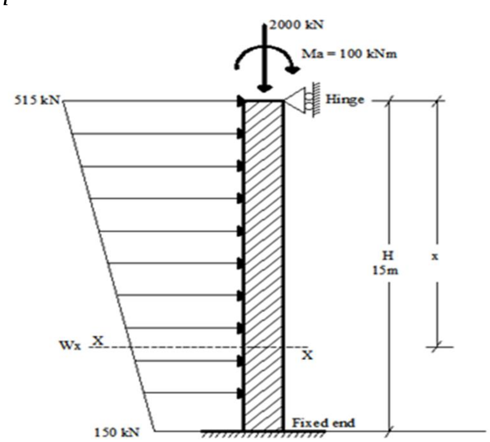

Figure 6 Trapezoidal force acting on complete height of pier

At, x = 0, hinged support
x = H, fixed support
For solid pier ***d*** = 3.0 m
For hollow pier, External diameter = 3.0 m,
Internal diameter = 2.4 m.
Span of bridge = 30m.
The values for base moment obtained by theoretically and by computer application (STAAD) are compared.

V. PARAMETRIC STUDY

Forces on pier are calculated as specified in IRC and the maximum moment is calculated in ***Table 1*** shown below. Using combined stress equation and keeping the stress constant, behavior of a solid circular and hollow circular section with combination of both is studied. The percentage reduction in volume for combination with solid and hollow pier is plotted for different heights of pier. The variation in area of cross section for different bending moments is studied.

Table1. Diameter of pier required for critical BM at base

Design Parameters					
Height(m)	Solid (mm)	Hollow (mm)		Combination (mm)	
15	2638	2760	1380	2638	1847
20	3114	3236	1618	3114	2180
25	3551	3675	1837.5	3551	2486
30	3976	4104	2052	3976	2783
35	4381	4514	2257	4381	3067
40	4759	4897	2448.5	4759	3331

A. *Comparative Bending Moment Analysis*

Table2. BM variation for 15m pier.

Bending Moment (Height 15m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
3	-4723	-4731	-4712	-4682	-4646	-4566	-4476
6	-5576	-5591	-5554	-5494	-5423	-5313	-5213
9	-3189	-3212	-3155	-3066	-2959	-2872	-2802
12	1808	1777	1853	1972	2115	2268	2328
15	8784	8747	8841	8990	9168	9256	9316

Graph1. BM variation for 15m pier

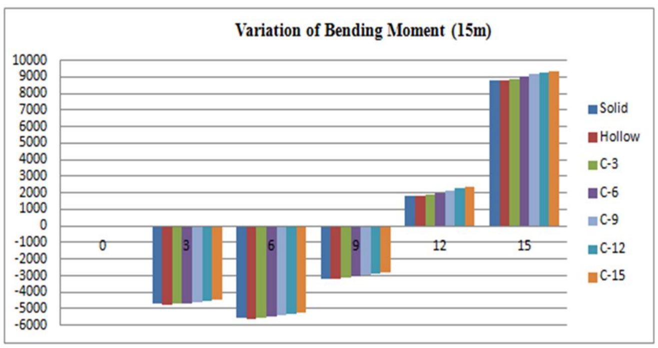

Table3. BM variation for 20m pier

Bending Moment (Height 20m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
4	-6580	-6591	-6564	-6523	-6473	-6361	-6236
8	-7769	-7790	-7737	-7654	-7555	-7402	-7263
12	-4443	-4475	-4396	-4271	-4122	-4001	-3904
16	2518	2476	2581	2747	2946	3160	3243
20	12238	12185	12317	12525	12773	12895	12979

Graph2. BM variation for 20m pier

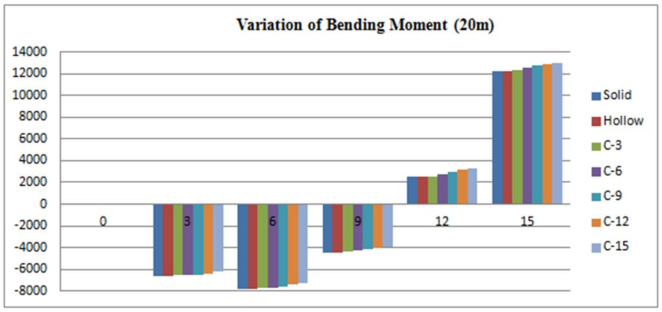

Table4. BM variation for 25m pier

Bending Moment (Height 25m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
5	-10230	-10247	-10206	-10141	-10064	-9890	-9695
10	-12078	-12111	-12029	-11900	-11745	-11508	-11291
15	-6908	-6957	-6835	-6641	-6409	-6221	-6069
20	3915	3850	4013	4272	4581	4912	5042
25	19027	18945	19150	19473	19859	20049	20178

Graph3. BM variation for 25m pier

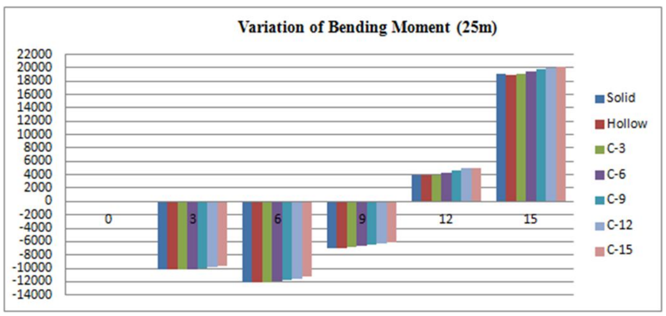

Table5. BM variation for 30m pier

Bending Moment (Height 30m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
6	-14806	-14830	-14770	-14677	-14565	-14313	-14031
12	-17480	-17528	-17409	-17222	-16999	-16655	-16342
18	-9998	-10069	-9891	-9611	-9275	-9003	-8784
24	5666	5572	5808	6182	6629	7110	7298
30	27537	27419	27715	28182	28741	29015	29203

Graph4. BM variation for 30m pier

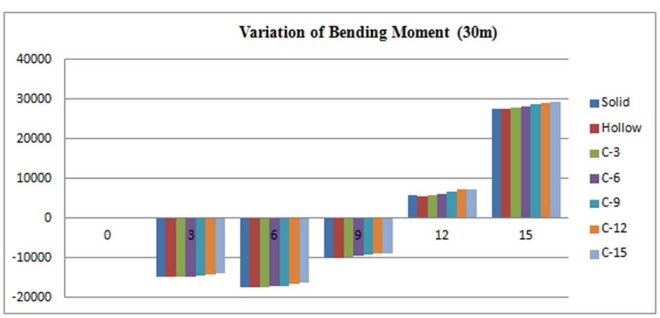

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Table6. BM variation for 35m pier

Bending Moment (Height 35m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
7	-20221	-20253	-20172	-20045	-19892	-19548	-19163
14	-23873	-23938	-23776	-23521	-23215	-22746	-22318
21	-13654	-13751	-13509	-13126	-12668	-12296	-11996
28	7738	7609	7932	8443	9054	9710	9967
35	37608	37447	37851	38489	39252	39627	39884

Graph5. BM variation for 35m pier

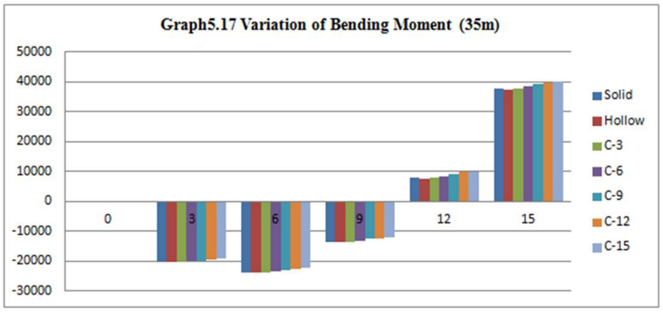
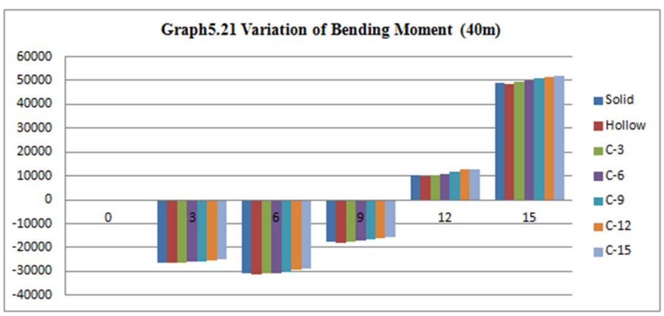


Table7. BM variation for 40m pier

Bending Moment (Height 40m)							
Section from top(m)	Solid	Hollow	C-3	C-6	C-9	C-12	C-15
0	0	0	0	0	0	0	0
8	-26302	-26344	-26239	-26073	-25874	-25427	-24926
16	-31053	-31137	-30926	-30594	-30197	-29587	-29030
24	-17761	-17887	-17571	-17073	-16477	-15993	-15604
32	10066	9898	10318	10982	11777	12630	12964
40	48918	48708	49233	50064	51057	51544	51878

Graph6. BM variation for 40m pier



B. *Comparative % Reduction in Volume*

Table8. % Reduction in volume variation for 15m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0	8.19E+07	5.73E+07	0	0	0	0	0
3			8.36E+06	5.56E+07	7.39E+07	9.80	-9.87
6			1.67E+07	4.92E+07	5.59E+07	19.60	2.07
9			2.51E+07	3.28E+07	5.79E+07	29.40	14.00
12			3.34E+07	1.64E+07	4.98E+07	39.20	25.94
15			4.18E+07	0.00E+00	4.18E+07	49.00	37.88

Graph7. Percentage Reduction in Volume (15m)

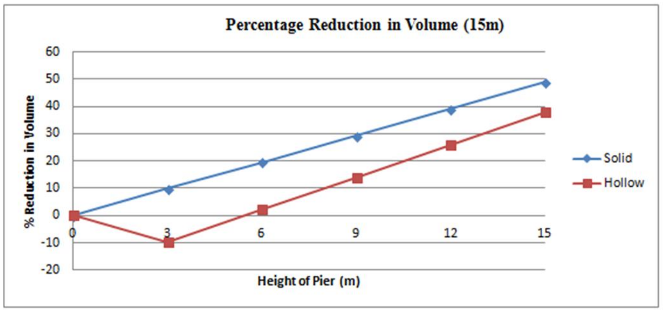


Table9. % Reduction in volume variation for 20m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0			0	0	0	0	0
4			8.58E+06	9.13E+07	9.99E+07	34.36	10.82
8	1.52E+08	1.12E+08	1.72E+07	5.85E+07	8.57E+07	43.73	23.54
12			2.57E+07	4.57E+07	7.14E+07	53.09	35.27
16			3.43E+07	2.28E+07	5.72E+07	62.46	48.99
20			4.29E+07	0	4.29E+07	71.82	61.72

Graph8. Percentage Reduction in Volume (20m)

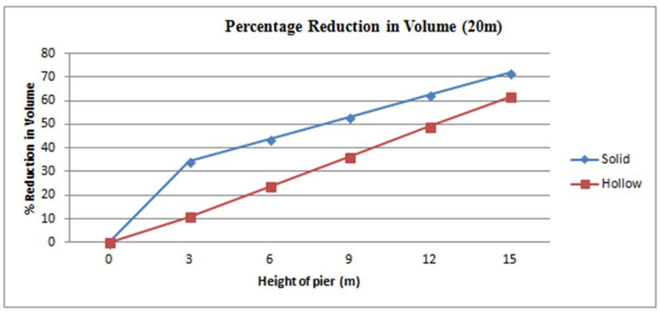


Table10. % Reduction in volume variation for 25m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0			0	0	0	0	0
5			1.12E+07	1.19E+08	1.30E+08	47.49	7.23
10	2.47E+08	1.40E+08	2.23E+07	8.91E+07	1.11E+08	54.98	20.46
15			3.35E+07	5.94E+07	9.29E+07	62.48	33.70
20			4.46E+07	2.97E+07	7.43E+07	69.97	45.94
25			5.58E+07	0.00E+00	5.58E+07	77.46	60.18

Graph9. Percentage Reduction in Volume (25m)

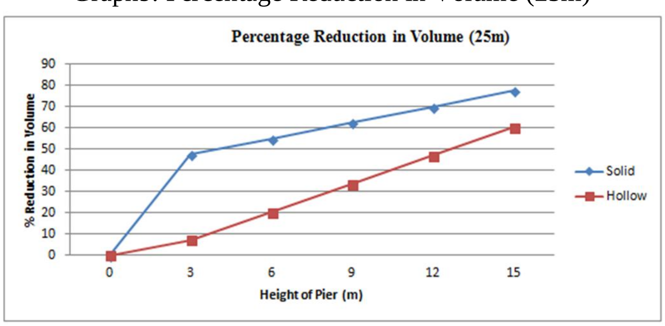


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Table11. % Reduction in volume variation for 30m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0	3.72E+08	2.70E+08	0	0	0	0	0
6			1.40E+07	1.49E+08	1.63E+08	55.25	39.74
12			2.80E+07	1.12E+08	1.40E+08	62.49	48.34
18			4.19E+07	7.45E+07	1.16E+08	68.74	55.94
24			5.59E+07	3.72E+07	9.31E+07	74.98	65.55
30			5.99E+07	0	5.99E+07	81.23	74.15

Graph10. Percentage Reduction in Volume (30m)

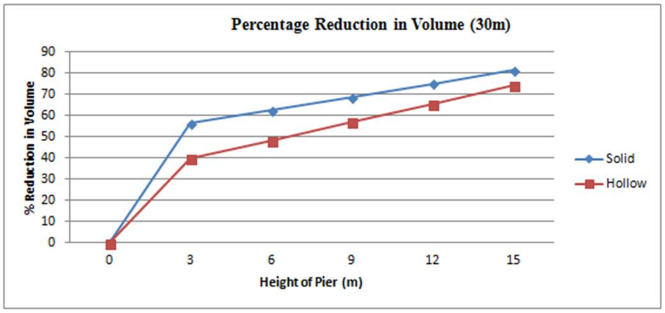


Table12. % Reduction in volume variation for 35m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0	5.27E+08	3.82E+08	0	0	0	0	0
7			1.70E+07	1.81E+08	1.98E+08	62.49	48.16
14			3.40E+07	1.36E+08	1.70E+08	67.85	55.56
21			5.09E+07	9.04E+07	1.41E+08	73.20	62.96
28			5.79E+07	4.52E+07	1.13E+08	78.55	70.35
35			8.49E+07	0	8.49E+07	83.90	77.75

Graph11. Percentage Reduction in Volume (35m)

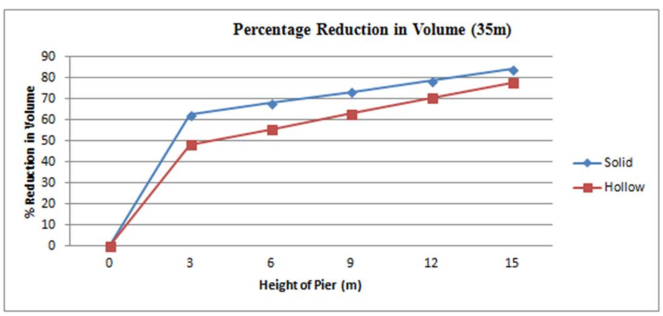
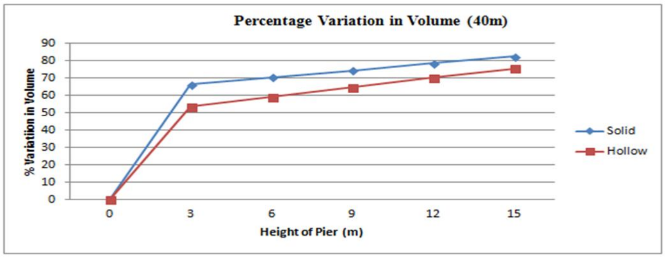


Table13. % Reduction in volume variation for 40m Pier

Percentage Variation in Volume of Pier							
Height	Solid	Hollow	Combination			%Reduction with	
H(m)	Vs	VH	Vh	Vs	Vc	Solid	Hollow
0	7.11E+08	5.13E+08	0	0	0	0	0
8			2.51E+07	2.13E+08	2.38E+08	65.47	53.53
16			5.02E+07	1.60E+08	2.10E+08	70.44	59.03
24			7.54E+07	1.07E+08	1.82E+08	74.40	64.53
32			1.00E+08	5.33E+07	1.54E+08	78.37	70.03
40			1.26E+08	0	1.26E+08	82.34	75.53

Graph12. Percentage Reduction in Volume (40m)



VI. CONCLUSION

A. As the height of the bridge pier increases the base B.M. value increases and critical B.M develops at the base of the pier.

B. Volume of concrete required increases with increase in base moment. However the rate of increase of volume of concrete required is milder for combination pier in comparison with solid and hollow circular pier.

C. The rate of increase for % reduction in volume of concrete varies from 49% to 83% for solid pier and 37% to 76% for hollow pier for height varying from 15m to 40m respectively.

D. Hence it can be concluded that as the height of pier increases the solid circular section and hollow circular section proves to be uneconomical as compared to combination of solid and hollow circular pier in section.

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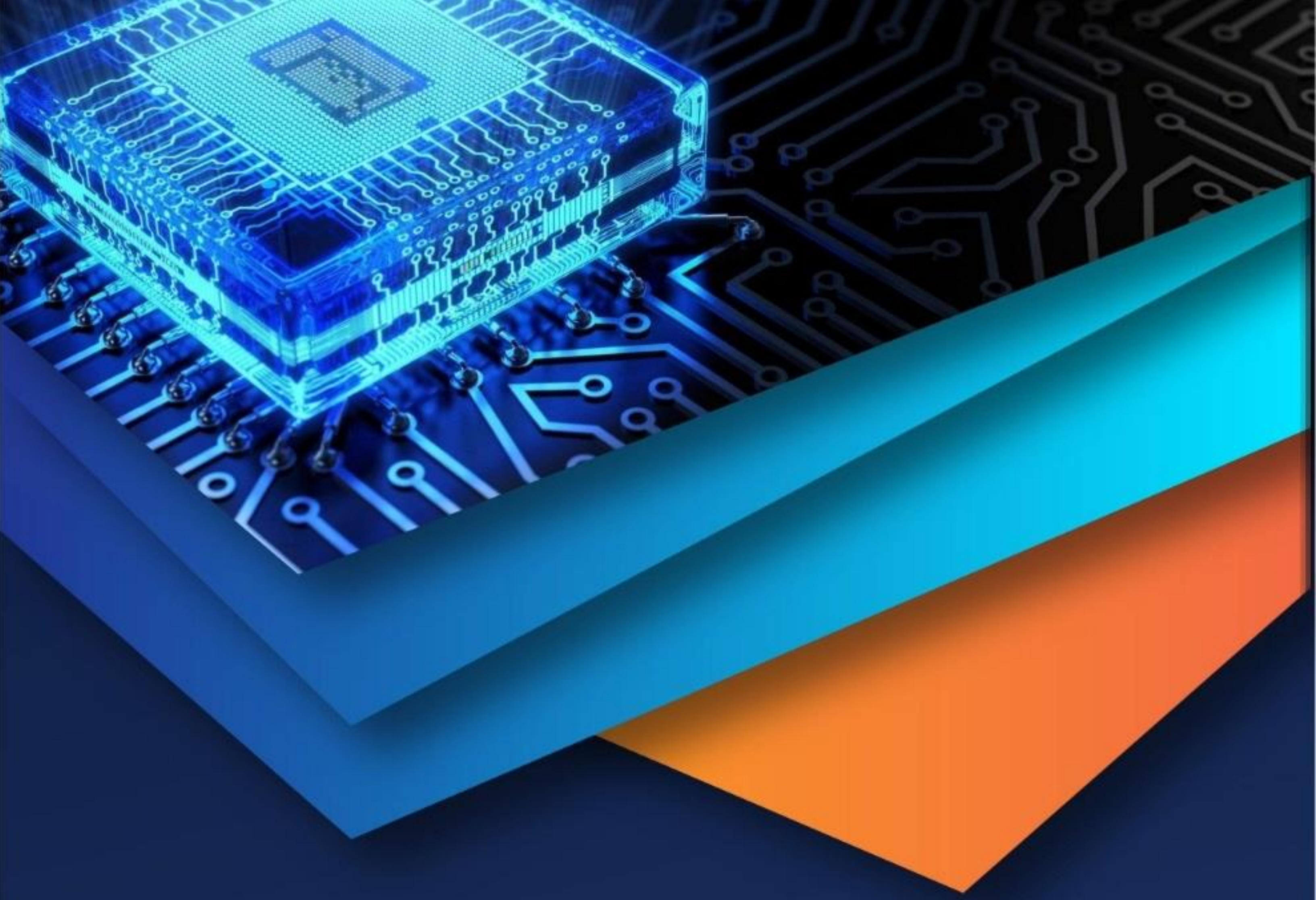

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