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Design and Performance Considerations for Buildings in Coastal and Offshore Environments

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Abstract

Buildings near coastal and offshore regions are exposed to extreme wind and seismic forces that govern structural design. In this study, a simplified assessment of wind and earthquake loads acting on a multistorey coastal building is presented. A wind velocity of 400 km/hr. is considered to represent severe cyclonic conditions. Using a unit weight of air of 12 N/m³, the cumulative wind thrust acting over a building height of 40 m and length of 30 m is evaluated. The building consists of four storeys with a storey height of 10 m and columns of 0.8 m width. While the direct wind thrust on an individual column is estimated as 24.11 tonnes, the total wind thrust on the building is calculated as 904.32 tonnes. With six columns spaced at 6 m along the building length, the additional load transferred to each bottom column is approximately 151 tonnes. A seismic event of magnitude 7 on the Richter scale is also considered, corresponding to a ground acceleration of 0.7 g (6.867 m/s²). The study highlights that the cumulative wind load governs the design of bottom columns in coastal buildings rather than local wind effects alone.

Keywords: Coastal buildings, wind thrust, seismic loading, bottom column design, offshore structures

INTRODUCTION

Coastal and offshore buildings are highly vulnerable to extreme environmental actions, such as offshore earthquakes, sudden increases in seawater level, and hydrodynamic pressures acting on substructure elements. Earthquakes occurring beneath the sea can cause a rapid increase in water depth and induce additional hydrostatic and hydrodynamic forces on foundations and columns, which significantly influence structural stability [1–3].

In the present study, an offshore seismic event was assumed to cause a rise in the water depth of 35 m. This increase in water depth generated a hydrostatic water pressure of 35 t/m² acting on the structure. In addition, the underground water pressure of equal magnitude is considered, as it depends directly on the depth of the water table. The velocity of water flow induced by seismic disturbance was assumed to be proportional to the water depth and was taken as 1.2 times the depth, resulting in a flow velocity of 42 m/s. The corresponding hydrodynamic thrust due to flowing water was estimated to be 90 t/m². Hence, the total water thrust acting on the structure was calculated as 160 t/m², accounting for hydrostatic pressure, underground water pressure, and hydrodynamic effects [4–5].

The vertical load contribution from the superstructure was also considered. The load on an intermediate column was taken as 60 t per story, resulting in a total load of 600 t for a ten-story building. An additional load of 151 t owing to wind action was included, leading to a combined structural load of approximately 2107 t on the bottom column. The self-weight of the column, calculated based on its dimensions and material density, was 6.144 t. Thus, the total load acting on a

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single column was 2113 t. Considering an additional 10% load contribution from the foundation, the total load at the foundation base was estimated to be 2324 t [6–8].

The lateral load effects were also incorporated by assuming that 21.7% of the total vertical load acted as a lateral force, resulting in a lateral load of approximately 604 t. Therefore, the allowable bearing pressure required is taken as 600 t/m², which exceeds the minimum design requirement. When combined with a water thrust of 160 t/m², the total load intensity acting at the foundation level was 760 t/m².

To ensure foundation stability, a compacted stone layer with a thickness of 600 mm was provided over the underlying saturated soil. The unit weight and angle of internal friction of the soil were assumed based on typical coastal conditions, with average values of $\gamma = 2$ t/m³ and $\varphi = 35°$. Based on the available bearing capacity of the underlying soil and the total load at the foundation base, including water thrust effects, the total load was calculated as 6804 t. Accordingly, a square foundation base of size 8.246 m × 8.246 m was required to safely support a single column under combined structural and environmental loading conditions [9–11].

Due to the earthquake, the sea rose to a depth of 35 m.
Hence, the thrust of water = 35 t/m^2

Thrust of underground water = 35 t/m^2 (depending on the depth of water).
Velocity of flow = 1.2 × 35 = 42 m/s.

Thrust of water due to the velocity of flow $= \frac{1000 \times (42)^2}{19.62} = 90\ t/m^2$

Hence, the total thrust of water = 35 + 35 + 90 = 160 t/m^2

Load on intermediate column = 60 t for one story. For 10 storey = 10 × 60 = 600 t
Additional load = 151 t
Hence, the total load on the bottom column = 600 + 1507 = 2107 t.

Weight of column (self-weight) = 0.8 × 0.8 × 4 24 = 6.144 t
Hence, the total load of one column = 2113 t
10% weight of foundation $= \frac{10}{100} \times 2113 = 211\ t$

The total load at the foundation base was 2324 t.
Lateral load = 0.217 × 2324 = 604 t
We required 600 t/m^2, greater than 504 t.
Hence, the load intensity due to the load on the column = 600 t/m^2 + 160 t/m^2 (thrust of water) = 760 t/m^2
Depth of foundation $D_f = \frac{760}{2} \times 0.073 = 28\ meter$

Strong foundation stone particles of 600 mm depth in a compact form are provided over the underlying saturated soil. Unit weight and ϕ of topsoil and bottom soil were taken.

The average value is $\gamma = 2$ t/m^3 and $\phi = 35°$. $\left[\frac{1-Sin\varphi}{1+Sin\varphi}\right]^2 = 0.073$

The foundation base size required depends on the available bearing capacity of the bottom soil.

$$\frac{Strength\ of\ stone\ particles\ +\ Underlying\ soil}{2} = 100t/m^2$$

$$\frac{10\ t/m^2\ +\ 190\ t/m^2}{2} = 100\ t/m^2$$

Total load at the foundation base due to the load on the column = 2324 t

Due to thrust of water = 160 × Depth of water × Width of column = 4480 t

Due to thrust of water = 160 × 35 × 0.8 = 4480 t

Hence, the total load at the foundation base = 4480 + 2324 6804 t

Hence, the foundation base required for one column is $= \frac{6804}{100}$ =68 m^2 = 8.246 m × 8.246 m.

Velocity of wind 400 Km/hr. =400 × $100060 \times 60 = 400036$ =111 m/sec

Thrust of wind =12 × (111)$219.62 = 7.536\ KN/m2$

where unit weight of air = 12 N/m^3

If storey height = 10

Height of building = 10 × 4 = 40 m

Width of column = 0.8 meter

Hence, the additional load at the bottom column due to wind thrust = 7.536 × 40 × 0.8 = 24.11 t.

Suppose an earthquake in the sea occurs at a 7 Richter scale.

10 Richter scale = 1 g

1 → $\frac{1}{10}$

7 → $\frac{7}{10} = 0.7\ g$

Ground vibration = 0.7 × 9.81 = 6.867 m/sec^2

Wind thrust is acting for a height of 40 m and a building length of 30 m.

Hence wind thrust 7.536 × 40 × 30 = 904.32 t

Spacing between columns = 6 m

Hence, the number of columns for a 30 m length of building = $\frac{30}{6} = 5 + 1$ = 6 columns.

Hence, load on one column $= \frac{9043.20}{6} = 1507\ t$

Hence, the load (additional on the bottom column) = 151 t, not 24.11 t.

Raft Foundation and Erosion Protection System

A reinforced cement concrete (RCC) raft foundation is adopted to safely distribute the high vertical and lateral loads arising from the combined wind, seismic, and hydrodynamic effects. Raft foundations are particularly suitable for coastal and offshore structures, where the soil strata are saturated, and the bearing capacity is influenced by water pressure and scour.

To prevent erosion of the underlying soil due to strong water currents and hydrodynamic thrust, a 2 m projection of the RCC raft is provided all around the foundation base. This projected portion acts as an apron, similar to those used in dam structures, and protects the foundation against scouring and uplift caused by flowing water.

The projected RCC base was designed to resist a water thrust of 160 t/m². To ensure stability against this thrust, the projected foundation was extended to a depth of 5.84 m below the foundation base. Considering the projection width of 2 m and the effective foundation base length of 7.28 m, the total load acting on the projected portion owing to the water thrusts

Based on this loading, the required thickness of the projected RCC base was determined to be 800 mm. Accordingly, an 800 mm thick RCC apron was provided around the entire foundation base to safely resist hydrodynamic forces.

To protect the underlying soil erosion, we provide a 2 m projection all around the foundation base, the RCC bed-like apron in the dam, to protect the underlying soil erosion.

The projected RCC base is to be provided to take the thrust of water = 160 t/m^2

Hence, the projected part (depth of foundation) $= \frac{160}{2} \times 0.073$ = 5.84 m below the foundation base projected RCC base is to be provided.

Since 160 t/m^2 acting on a 2m projection and 7.28 m length of the foundation base size, the load is 160 × 2 × 7.28 = 2330 t.

Thickness of projected RCC base $= 2330 \times 1000 \times 107.28 \times 1000 \times t = 10100 \times 40 = 4$

29120 t = 23300000

t = 800 mm thickness of the projected R. C. C. bed all around the foundation base is to be provided.

The overturning and restoring moments were checked.

Load on column = 2113 t

Thrust of water 160 t/m^2 = 160 × Depth of water × 0.8 = Width of column

Thrust of water 160 t/m^2 = 160 × 35 × 0.8 = 4480 t

Hence, the total load on the bottom column = 4480 + 2113 = 6593 t.

Lateral load = 0.217 × 6593 = 1431 t

Overturning moment = 1431 × 4 = 5723 t · m

Restoring moment:

Average strength of topsoil and bottom soil $= \frac{10+100}{2} = 55\ t/m^2$

Restoring moment : Depth of foundation× Width of column × 55 × $\frac{28}{2}$ = 17248 t-m < 4546 t-m.

Restoring moment: 28 × 0.8 × 55 × $\frac{28}{2}$ = 17248 t-m < 4546 t-m.

Safe.

We can make a further strong foundation by providing 600 mm depth of compact sand:

Strength of topsoil and bottom soil $= 10 + 190 \times \text{Stone particles} = \text{Sand}\ t/m2$

$$= 10 + 190 \times 1653 = 122\ t/m2$$

Hence, strength of topsoil and bottom soil $= 10 + 190 \times 1653 = 122\ t/m2$

Ground Improvement Measures

To further enhance the foundation stability and bearing capacity, a 600 mm thick layer of compacted sand was provided above the stone particle layer. This ground improvement measure increases shear resistance, improves the distribution of load, and reduces settlement under combined loading. The combined use of stone particles and compacted sand ensures improved strength of the top and bottom soil layers, making the foundation suitable for extreme coastal and offshore-loading conditions.

Buildings near coastal areas are subjected to earthquake load and water thrust.

The thrust of the seismic force =, since ground vibration occurs below ground level for the entire area of the building (30 m × 30 m) for a foundation depth of 13 m.

Using P = mf = 30 × 30 × 13 × 1850 × 6.867 = 148636 t

This is because 6 × 6 = 36 columns.

Hence, the load on one column due to seismic force $= \frac{148636}{36}$ is not considered.

$D_{f} = 13$

Hence, the seismic force = 13 × 0.8 × 0.8 × 1850 × 6.867 = 106 t

Where, 13 m = depth of the foundation, 0.8 × 0.8 m = cross-sectional area of the column.

1850 kg/m^3 = Unit weight of soil ground vibration = 6.867 m/sec.

Hence, the additional load due to the seismic force on the column (bottom). 6.144 = Weight of column

= 600 + 106

= 706 t + 6.144 = 712 t

10% weight of foundation $= \frac{10}{100} \times 712 = 71\ t$

Total load at the foundation base = 712 + 71 = 783 t

The lateral load at the base was 0.217 × 783 = 170 t; hence, we require 190 t/m^2 bearing capacity of 190 t/m^2 for the soil load intensity owing to the load on the column = 190 t/m^2. Thrust of water → Due to earthquake in sea = 160 t/m^2

Hence, the total load intensity = 190 + 160 = 350 t/m^2

Hence, the depth of the foundation is 13 m for $\gamma = 2$ t/m^3 and $\phi = 35°$.

Foundation base size = 7.28 m × 7.28 m, and like wind thrust is provided.

RESULTS AND DISCUSSION

To protect the underlying soil from erosion, we provide a 2 m projection of the RCC base below the foundation base of 800 mm thickness.

- Hence, the depth of the foundation is 13 m, and the foundation base size is 7.28 m × 7.28 m for one column. In addition, a strong foundation is needed; that is, sand (compact) of 600 mm depth is provided over the underlying soil, and over the sand layer, 600 mm depth of compact stone particles will be provided.

- Required load intensity for the load on the column and seismic force taken due to the earthquake at sea.
- A strong foundation (raft foundation) is provided.
- To protect the underlying soil erosion, a 2 m projection of the R. C. C. bed of 800 mm thickness below the foundation base, all around the foundation base, is provided.

Penetration of Water in the Dam

Depth of water = 35 m

Penetration into the dam = 0.6 × 35 = 21 m (laterally)

If the top width = 15 m.

Bottom width of dam = 30 m.

Consequently, the soil strength is reduced.

Load of dam = $\frac{15+30}{2} \times 45 \times$ height per meter $\times\ run = 1873\ t$

$$= \frac{15+30}{2} \times 45 \times 1 \times 1850 = 1873\ t$$

Load due to vehicle on dam = 3.5 m × 1.2 m = 70

1 $m^2 \rightarrow \frac{70}{4.2}$

Length of vehicle × Width = 16 m × 3 m

$$= \frac{70 \times 16 \times 3}{4.2} = 800t$$

Total load of dam = 1873 + 800 = 2673 t

10 % weight of foundation $=10100 \times 2673 = 267\ t$

The total load at the foundation base was 2673 + 267 = 2940 t.

The lateral load at the foundation base was 0.333 × 2940 = 979 t.

We require a t/m^2 bearing capacity of 1000 t/m^2.

Hence, the load intensity due to the dam was 1000 t/m^2

Rocky strata are required.

Hence, a raft foundation with a heavy load is constructed.

Thrust of water = 35 t/m^2 (depth of water = 35 t)

Underground water thrust = 35 t/m^2

The velocity of flow was 1.2 × 35 = 42 m/s.

Thrust $=1000 \times (42)219.62 = 90\ t/m2$

Total thrust of water = 160 t/m^2

Hence, the total load intensity was 1000 + 160 = 1160 t/m^2

Topsoil = 1.6 t/m^3 = Unit weight

Bottom soil = 2.64 t/m^3 (strong foundation, that is, underlying soil stone particles of 600 mm depth compact are to be provided).

Average $\gamma = \frac{1.6\ +\ 2.64}{2} = 2.12\ t/m^3$

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- The load is applied from top to bottom; if a strong foundation is made, there will be no problem.

Depth of the foundation needed:

$D_f = \frac{1160}{2.12} \times 0.073$ ϕ = 35° Average taken

$\left[\frac{1-Sin\varphi}{1+Sin\varphi}\right]^2 = 0.073$

= 40 m depth of foundation needed.

The foundation base size is needed for the available bearing capacity of soil at the foundation base, a strong foundation →overlying soil → sand layer + stone particles of 600 mm depth in compact form and the strength of rocky strata 330 t/m^2

(Underlying soil) Hence, $= \frac{330\ +\ 165+190}{3} = 228\ t/m^2$

Total load at the foundation base owing to the load on the dam = 2940 t

Thrust of water = 160 t/m^2 acting on 35 m depth of water and per meter length of dam Hence, 160 × 35 × 1 = 5600 t.

Hence, the total load at the foundation base = 2940 + 5600 = 8540 t.

Hence, the foundation base size required $= \frac{8540}{228} = 37\ meter$

Hence, a foundation width of 40 m at the base is to be provided.

Settlement

Owing to the penetration of water = 0.6 × 35 = 21 m, the strength of the soil will be reduced for the dam. Suppose in dry conditions, bearing capacity = 30 t/m^2.

For a bearing capacity of 30 t/m^2, bearing capacity 30 = 1.85 × D × 9

ϕ = 30° $= 1.85 \times \left[\frac{1-Sin\varphi}{1+Sin\varphi}\right]^2 \times 9$

Depth for 30 t/m^2

$$D = \frac{30}{1.85\ \times\ 9} = \frac{30}{16.65} = 1.80\ meter$$

After the penetration of water in the dam, the bearing capacity is lowered by 50% loss of bearing capacity = 15 t/m^2. For this loss, we have to provide more depth of foundation.

D_f (more depth of foundation needed) =151.7 × 1−−sin(201°) +sin(202°)
151.7 × 1−0.3421.3422

More $= \frac{15}{1.7} \times \left[\frac{0.658}{1.342}\right]^2$

$= \frac{15}{1.7} \times 0.240$ = 2.12 m. More depth of foundation is needed.

Hence, we must provide a foundation depth of 42 m.

Settlement → For 30 t/m^2

Depth = 1.80 meters

For 15 t/m^2

Depth $=151.85 \times 0.111 = 0.90\ meter$

For a higher bearing capacity, a greater depth of foundation is required.

Change in pressure 3.0 – 15 = 15 t/m^2

$=15 \times 1000100 \times 1000 = 1.5\ kg/cm^2$

Change in depth = 1.80 – 0.90 = 0.90 meter = 0.90 × 100 = 90 cm.

Settlement = 1.5 × 90 × $\frac{0.35}{100}$ = 5 mm <50 mm

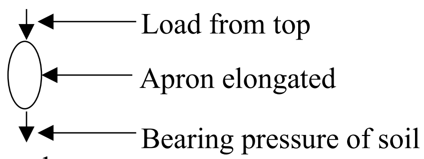
Hence, okay

A 10 m projected RCC base is to be provided around the foundation base to take the thrust of water.

Depth of foundation for apron:

Thrust = 160 t/m^2 acting on a 20 m projection from the foundation base and a 1 m length of dam.

Hence thrust = 160 × 20 × 1 = 3200 t



M40 grade concrete

Hence, $3200 \times 1000 \times 1020000 \times t = 10100 \times 40 = 4$

80000 t = 32000000

$t = \frac{32000000}{80000}$ = 400 mm thickness of apron [projected RCC bed] is provided below the foundation base so that scouring of soil below the foundation base should not take place.

Depth of foundation for apron (projected RCC bed) → since apron is provided for thrust of water and thrust of water is 160 t/m^2

Hence, the depth of the foundation for the apron is

$Df=1602.12 \times 0.073 = 5.51\ meter$

Hence, an apron should be provided at a depth of 5.51 m below the foundation base with a thickness of 400 mm.

The required depth of the foundation and the required foundation base size are to be provided.
In addition, an apron should be provided below the foundation base to prevent scouring of the underlying soil from taking place.

$= \frac{30}{6}$

CONCLUSION

In this study, the combined effects of the column load, wind thrust, and water thrust were considered to evaluate the structural and foundation behavior of a coastal building. The analysis showed that cumulative lateral and vertical loads significantly influenced the design of bottom columns and foundations in offshore and coastal environments.

To protect the underlying soil from erosion and scour caused by hydrodynamic forces, a 2 m wide projected RCC bed was provided all around the foundation base. This projected foundation acts as an effective apron, enhancing stability and ensuring the safety of the structure under extreme environmental loading conditions.

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