Design of Combined Pile-Raft Foundation (CPRF) Under the Loads of Reactor (Containment) and Auxiliary Buildings of a Nuclear Power Plant

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***Abstract*— There have been numerous studies on the designing of a pile raft foundation for nuclear power plants. However, the main focus of this study is the design of pile raft foundations for both containment and auxiliary buildings. The total area of the plant is divided into 4 quadrants where each quadrant is separated by 1m of dilatation. Since there are limited studies on the use of dilatation in pile raft foundations, this paper focused on the effectiveness of dilatation in pile-raft foundations of superstructures. This paper explores the design of five distinct rafts, one for each quadrant of the nuclear power plant, with each foundation section having specific pile arrangements and thickness. The central raft for the reactor building bears the highest load and requires thicker reinforcement. Advanced design methodologies were employed, including software like GEO5 software for geotechnical analysis and Tekla Structural Designer for structural modelling. In particular, the paper incorporates pile spacing of 2.5 meters and 5 meters for the containment and auxiliary buildings, respectively, with pile lengths of 20 meters for the containment and 15 meters for the auxiliary buildings. The findings demonstrate that with the combination of pile-raft, the differential settlement can be significantly reduced. The research concludes that dilatation in CPRF design can effectively mitigate the risks associated with foundation movement, ensuring structural integrity and long-term operational safety. Finally, the result of the pile and raft design shows that the total load of 26000 kN will be safely carried by the pile-raft foundation.**

***Index Terms*— Pile foundation, pile-raft, containment building, auxiliary building, nuclear power plant, construction**

I. INTRODUCTION

With the increase of the world's population growth, the share demand for nuclear power is growing massively. According to International Energy Agency (News - IEA, 2023), the energy demand of business and private households will increase by around 60% by 2030. To be able to adopt energy supply countries have invested massively in building nuclear power plants. As an example, 75% of France's electricity is generated by nuclear power plants [1]. Another reason for investing in nuclear energy is coming from contributing positively to climate change and zero carbon emissions. According to Électricité de France (EDF) where a single peanut size uranium will produce energy as 800kg of coal [2]. According to Nuclear AMRC | Nuclear Advanced Manufacturing Research (AMRC), to meet the commitment of net greenhouse gas by 2050, the UK government needs a new method of generating low-carbon electricity. The UK government is aiming to meet to commitment by 2050 by moving from fossil fuels to electric power consumption.

The construction of nuclear power plants is an incredible complex where it requires a huge amount of investment to build. The plant is divided into many small and large buildings such as a reactor building (containment building), auxiliary building, fuel storage building, control room, administrative building, etc. Among these buildings, the containment buildings and auxiliary building are the most important in a nuclear power plant where the containment building protects the outdoor environment from radiation and the auxiliary building is the main control and storage buildings. Therefore, a combined pile raft foundation (CPRF) is preferred for the containment and auxiliary buildings.

In countries like the United States and France, more than the half of NPPs is built upon soft rock [3]. In some cases, NPPs are also built upon relatively soft soils such as Kashiwazaki-Kariwa and Vogtle nuclear power plants [3]. The occurrence of earthquakes is unavoidable and causes an unpredictable threat to the plants. For instance, the Kashiwazaki-Kariwa nuclear power plant was struck by a Niigata Prefecture strong earthquake and the plant suffered from beyond the design of earthquake motion which caused serious damage to the upper part of the structure [4].

In most cases, the nuclear power plant is a rock layer with a raft type of foundation such as the Jingyu power plant in China. However, due to the limited number of suitable sites, and with the increase in the demand of nuclear power plants, it is inevitable to construct the nuclear power plants on soft soils [5].

This study will also consider the effect of dilatation between the 4 quadrants of the nuclear power plant pile-raft foundation to reduce the total damage of structure in the event of natural and human disasters. Therefore, the present study aims to design a combined pile raft foundation (CPRF) under the loads of containment (reactor building) and auxiliary buildings of a nuclear power plant using Eurocode and British standards. To achieve this aim, the necessary dimensions of the structure and foundation will be identified for further calculations and program analysis. Furthermore, auxiliary and containment buildings of the plant will be modelled using Tekla structural designer software, and pile foundation will be designed using GEO5-pile software.

Finally, at the end of the analysis the 5 different pile-raft foundations will be designed according to the imposed load of the structure which reduces the risk of any damage to the adjacent buildings in the event of any incident.

II. MATERIALS AND METHODS

Containment Building

To prevent the spread of nuclear radioactive materials outside of the containment building into the environment, it is a must to have multiple nuclear power plant barriers [6]. Although the configuration, size, shape, and design of a containment building may vary significantly depending on the size and location of the plant, the principle and usage of the containment building in a nuclear power plant remain the same as the tightness of the leakage is assured by gaskets, nonmetallic seals and other metallic components which are either bolted or welded [7].

The nuclear reactor as well as the cooling system is located in containment building of a nuclear power plant. The containment building is pressure- retaining reinforced concrete and metal lined, where in some cases post-tension may also be used. The pressured induced force of the nuclear reaction is contained by the strong cylindrical reinforced concrete wall with an ellipsoidal or hemispherical dome at the top and a flat base slab where the leakage-tightness is prevented by a 6mm relatively thin steel plate [7]. The containment building walls have an additional prestressing system placed where in the dome a non-adherent tendon is placed [8].

According to [8] the total height of the containment building can be taken as 63.4m with an interior diameter of 40m. The height of the cylinder is 43.4m, the cylindrical wall thickness is 1.15m, the thickness of the dome is 0.95m, the thickness of inner steel layer is 6.5mm, and the thickness of the foundation slab is 3m [8]. Also, other researchers like Thusa mentioned that the wall thickness of the containment building varies from 1.1 to 1.7 meters [9].

Auxiliary Building

The Auxiliary building of a nuclear power plant is often located next to the containment building [10]. The building consists of safety systems related to nuclear reactors, for instance; nuclear radioactive waste, the control system for chemicals, and the emergency system of cooling water [10].

The general geometry of an auxiliary building of a nuclear power plant depends on how many turbines are being installed in the plant. Therefore, a typical PAB (Primary Auxiliary Building) cross-section can be defined as 73,154mm x 66,446mm with a total height of 37,491 mm where all the concrete beams, columns, slabs and walls are reinforced with rebars [11].

Generally, the auxiliary building is a box-shaped structure with shear wall constructed of strong reinforced concrete [12]. The internal wall thickness ranges from 0.3 to 1.2m depending on the usage of the area, which generally resists the applied loads such as dead load, live load and applied load as well as provide a shield against radiation [12]. The exterior walls range from 0.45 to 1.2m where the thickness of the wall protects piping and safety equipment from any external emergency events [12]. The thickness of the base may vary from 1.8 to 8.2 m, and the roof slab's thickness is about 0.45m also the floor slab ranges from 0.3 to 0.9m in thickness [12].

Combined Pile-Raft Foundation

In most cases, the raft foundation can be sufficient to support the bearing capacity of the structure while the differential structure settlement might exceed the limit. Therefore, for such loads combined pile-raft foundation (CPRF) is being used to transfer the superstructure heavy load to soil and reduce the differential settlement [13]. Furthermore, when the total load of the super structure is being transferred through the piles, a large number of piles is required depending on the type of the resisting soil condition [13].

Apart from numerous benefits of the CPRF type of foundation over conventional group pile foundation, the main aspect of benefit of the CPRF system is the sharing and distribution of total structure load by the raft along the piles which significantly reduces the number of piles needed to support the megastructure without violating the serviceability and safety aspect of the system [14].

The pile spacing as well as length depends on the intensity of the imposed load by the structure to the pile raft. Although, researchers like [15] believes that the pile spacing can be taken as 3.949m in X and Y directions for both contentment and auxiliary buildings while the diameter of pile varies between 1.2m-1.9m. Other researchers believe that pile spacing in a NPP's in both X and Y direction can be taken as 3D, 3.5D, and 4D [16].

In this study, the length of the piles in contentment building is 20m and spacing in both X and Y direction is taken as 2.5m. For the auxiliary building, the pile spacing in both X and Y axis is taken as 5 meters where the length of each pile is 15 meters based on the [16], research.

Megastructures need to be separated by dilatation in between the building's sections. Dilatation is a method in construction where the dilatation joint can absorb the contraction as well as expansion of the building due to temperature change, and vibration due to earthquakes. Since the reactor building (Containment building) has a diameter of 40-50 meters, the adjacent building (Auxiliary building) needs to be constructed on a separate foundation. The foundation of the two buildings is not in direct contact and is separated by 1m where in reality the clearance between the buildings is (typically 0.1-0.2m) [17].

In this study a 121x121m summing to a total area of 14,641 m^2 for both containment building and auxiliary buildings is considered as shown in Figure 1. The total areas are divided into 4 sections, where each section is separated by 1m of dilatation. All dimensions are in meters.

The height of the containment building is considered to be 47 meters. The wall thickness of the containment building is considered to be 1.6m as shown in Figure 1.

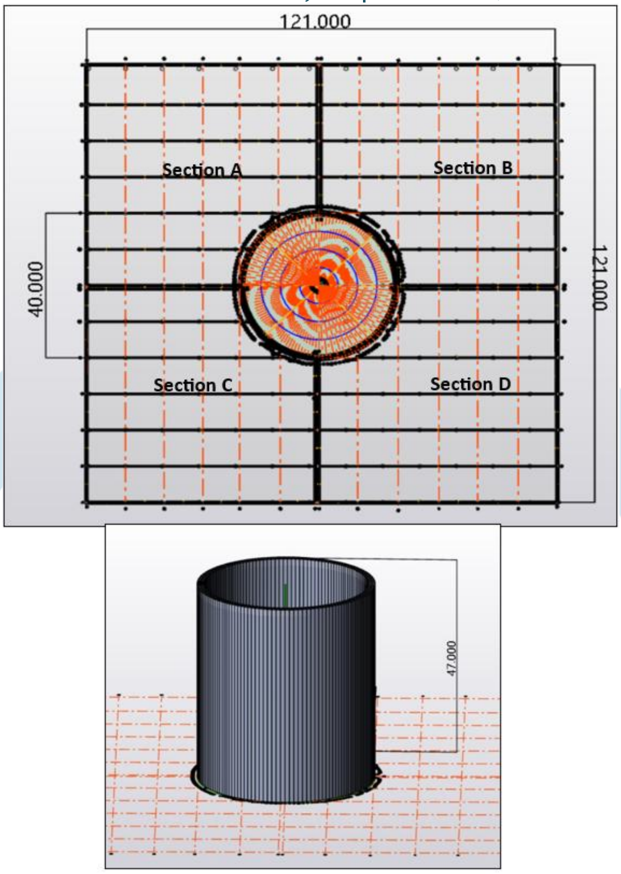

Figure 1: Section Deviation of Nuclear Power Plant and Containment Building Design

The exterior wall thickness is taken as 600mm where the interior wall thickness is taken as 450mm. The thickness of slab between each floor is considered to be 350mm. For the initial design the thickness of the raft is considered to be 3m. The spacing between each pile is 2.5 m in containment building and 5m in auxiliary building. The length of the piles in the contentment building is considered to be 20m. For the auxiliary building the length of each pile is considered to be 15 meters.

Design Steps

To show the loading on the raft as well as the piles in the first step is to design the containment building as well as auxiliary building. In the second step, a 3m thick raft is designed for four side rafts and a 4.5m raft for contentment building. The piles have been placed in contentment and auxiliary buildings accordingly. In the third step, the total load of the containment and auxiliary building on the raft has been calculated. The design is also based on trial-and-error method by changing the pile and raft parameters.

In the analysis three loading has been considered, dead load, wind load, and earthquake load. In earthquake, all other parameters such as the time period and intensity of the earthquake are automatically calculated by the Tekla Structural Designer software. At the end of the earthquake analysis, the result shows that the maximum period of the earthquake is 2.5 seconds. Using the geographical data of Hinkley Point C NPP where the site altitude is taken by 272 m, and importantly the wind velocity is considered to be 23.4 m/s. Other parameters such as the height of the structure, air density, season factors, as well as probability factors are calculated by the software automatically. The result of the wind load shows that the maximum wind load is calculated as 1.4 kN/m^2.

III. RESULTS AND DISCUSSION

The maximum axial load analysis is computed using first-order linear computation as shown in Figure 2.

The maximum axial load is found to be 25815.5 kN and the maximum bearing stresses are found as 284.7 kN/m^2. The maximum bearing stress, as well as maximum axial load, are both located in the contentment building area.

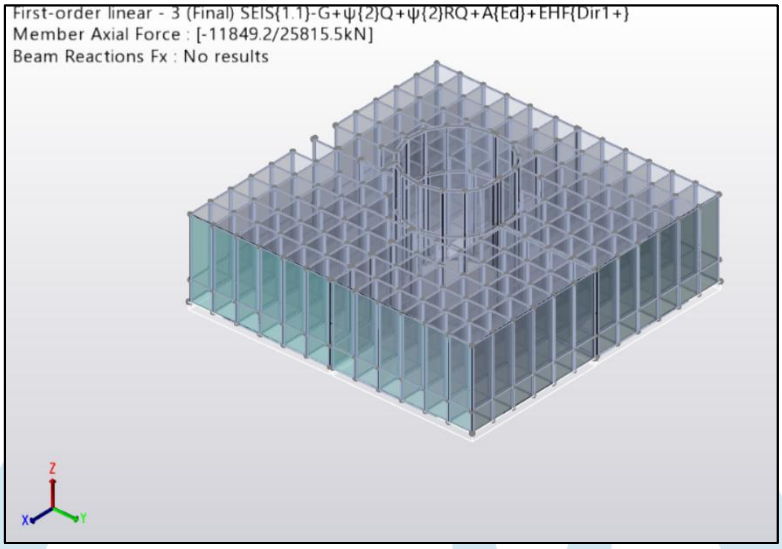

Figure 2: Maximum Axial Load

The maximum load occurs on the upper part of the contentment building. The location of the maximum load was expected to the near the contentment building since the thickness of the contentment building wall is taken as 1600 mm where the height reaches around 47 meters. The maximum stress is shown in the Figure 3.

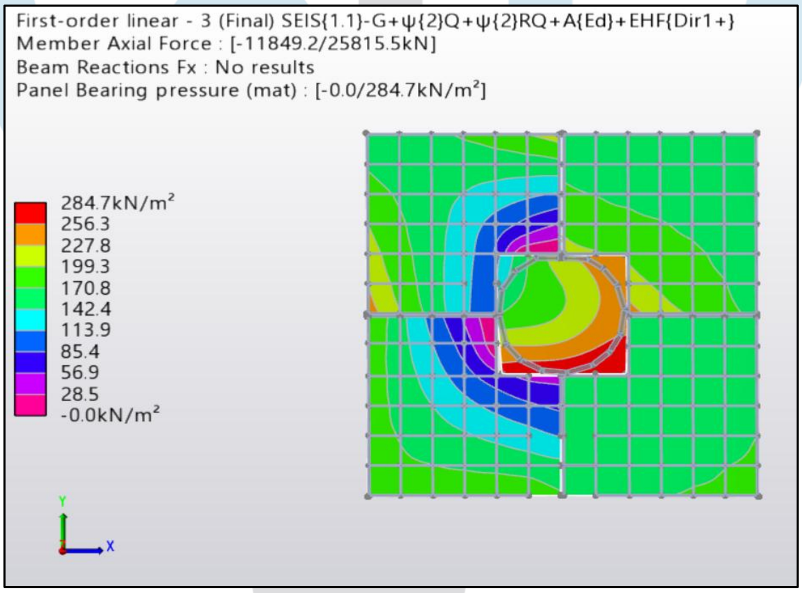

Figure 3: Maximum Raft Pressure

Initially, the five rafts have been failed due to the excessive load of the structure, however, the total capacity of the of the raft will be calculated using the Tekla Structural Designer and GEO5-Slab software's as well as soil bearing capacity. The soil-bearing capacity will be added later in the Tekla Structural designer program.

Generic Soil Model

The generic soil model has been developed using the borehole record obtained from the British Geological Survey. Figure 4 represents the generic soil model.

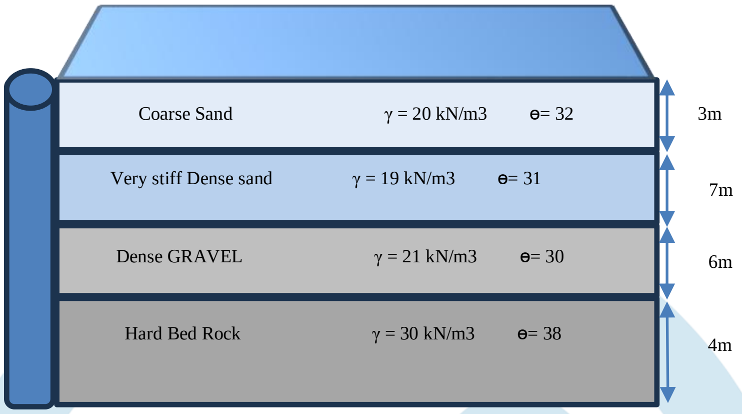

Figure 4: Soil Generic Model

The generic soil profile will be used in the analysis of the 20-meter pile located in the containment building with an axial load of 26000 kN.

These parameters are including unit weight, passion's ratio, angle of friction, density, and skin friction resistance factor.

The borehole record does not include the presence of a water table, however in the analysis section firstly it has been assumed that the borehole is dry, later in order to be more realistic the presence of water is assumed in the depth of 12m below the ground level.

Pile Analysis

The pile analysis has been conducted using GEO5-Pile software. In order to reduce the failure mechanism in both shear and moment of the pile has been confined with reinforcements. In order to increase the bearing capacity of the piles 15 bars with 30mm diameter have been placed around the 1-meter circular pile. To be able to reduce shear failure 16mm bar is to hold the main pile reinforcement with a spacing of 200mm.

The effect of the water table in 12 meters below the ground level is considered to be in the analysis of bearing capacity. The analysis result shows that the skin friction is 821.35 kN where the bearing capacity in the base of the pile is 25531.72 kN and the total capacity of the pile is 26353.08 kN. The result shows that the pile will carry the maximum load of 26000 kN safely.

The GEO5-pile has used BS standards which state that the maximum settlement of each pile should not exceed 25mm. At the end of the analysis, the result shows that the maximum settlement of the pile is 6.5mm. The reason for the less settlement of the pile is due to the presence of hard bedrock soil at the depth of 20m.

Bearing capacity analysis of the soil

In soil bearing capacity analysis the parameters such as the unit weight of soil and the angle of the friction will be taken from the GEO5-pile software.

Calculation of effective stress using the data in Figure 4:

Using the effective stress formula where:

$$\sigma = z * \gamma \qquad (1)$$

Where:
d = is the distance from the surface
γ = is the unit weight of the specific soil

When z = 3m, $\sigma_1 = 3(20) = 60\ kN/m^2$
When z = 7m, $\sigma_2 = 60 + 7(19) = 193\ kN/m^2$
When z = 6m, $\sigma_3 = 193 + 6(21) = 319\ kN/m^2$
When z = 4m, $\sigma_4 = 319 + 30(4) = 439\ kN/m^2$

In total, the vertical effective stress is calculated as 439 kN/m^2

Calculation to bearing capacity:

In the calculation of the bearing capacity the revised Terzaghi bearing capacity equation is being used where the surcharge = 0, Df = 0, and c' = 0 [18].

$$q_u = q * N_q * F_{qs} * F_{qd} * F_{qi} + \frac{1}{2} * \gamma * B * N_\gamma * F_{\gamma s} * F_{\gamma d} * F_{\gamma i} \qquad (2)$$

Equation 2 - Revised Terzaghi bearing capacity equation

Where:
q_u = Ultimate bearing capacity
γ = The unit weight of water
B = is the width of the raft
N_γ = Terzaghi bearing capacity factor
F_{qs} = F_{qi} = $F_{\gamma i}$ = Inclination factors

$F_{qd} = F_{\gamma d}$ = Depth factor
$F_{qs} = F_{\gamma s}$ = Shape factor

Using the 3-meter depth where the angle of friction is 32 degrees, the Terzaghi equation factors are as follows where the parameters are unitless:
$N_c = 32.67$ $N_q = 23.18$ $N_\gamma = 30.22$

The shape, depth and inclination factor formulas obtained from [18].

Shape factors:

$$F_{cs} = 1 + \left(\frac{B}{L}\right)\left(\frac{N_q}{N_c}\right) \quad (3)$$

$$F_{qs} = 1 + \left(\frac{B}{L}\right)\tan\phi' \quad (4)$$

$$F_{\gamma s} = 1 - 0.4\left(\frac{B}{L}\right) \quad (5)$$

DeBeer 1970 Shape factor equations

Depth factors:

$\frac{D_f}{B} \leq 1$

$For\ \phi = 0$:

$$F_{cd} = 1 + 0.4\left(\frac{D_f}{B}\right) \quad (6)$$
$$F_{qd} = 1$$
$$F_{\gamma d} = 1$$

$For\ \phi' > 0$:

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c \tan\phi'} \quad (7)$$

$$F_{qd} = 1 + 2\tan^2\phi'(1 - sin\,\phi')^2\left(\frac{D_f}{B}\right) \quad (8)$$
$$F_{\gamma d} = 1$$

If $\frac{D_f}{B} > 1$
$For\ \phi = 0$:

$$F_{cd} = 1 + 0.4\tan^{-1}\left(\frac{D_f}{B}\right) \quad (9)$$
$$F_{qd} = 1$$
$$F_{\gamma d} = 1$$

For $\phi' > 0$:

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c \tan\phi'} \quad (10)$$

$$F_{qd} = 1 + 2\tan^2\phi'(1 - sin\,\phi')^2\tan^{-1}\left(\frac{D_f}{B}\right) \quad (11)$$
$$F_{\gamma d} = 1$$

Inclination factors:

$$F_{ci} = F_{qi} = \left(1 - \frac{\beta^o}{90^o}\right)^2 \quad (12)$$

$$F_{\gamma i} = \left(1 - \frac{\beta}{\phi'}\right) \quad (13)$$

β = Inclination factor of the load on the foundation with respect to the vertical
Shape factors calculation:

$$F_{CS} = 1 + \left(\frac{3}{60}\right)\left(\frac{N_q}{N_c}\right) \Longrightarrow \quad 1 + \left(\frac{3}{3}\right)\left(\frac{23.18}{32.67}\right) = 0.035$$

$$F_{qS} = 1 + \left(\frac{B}{L}\right)\tan\theta \Longrightarrow \quad 1 + \left(\frac{3}{60}\right)\tan 32 = 1.031$$

$$F_{\gamma S} = 1 - 0.4\left(\frac{B}{L}\right) \Longrightarrow 1 - 0.4\left(\frac{3}{60}\right) = 0.98$$

Depth factors calculation:

$$\frac{D_f}{B} \Longrightarrow \frac{3}{60} = 0.05$$

Since $\frac{D_f}{B}$ <1 then the second case of depth factor formula is being used.

$$F_{qd} = 1 + 2\tan\theta\,(1 - \sin\theta)^2 \left(\frac{D_f}{B}\right) \Longrightarrow 1 + 2\tan 23\ (1 - \sin 32)^2 \left(\frac{3}{60}\right) = 1.016$$

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c \tan\theta} \Longrightarrow 1.3 - \frac{1 - 1.016}{32.67 \tan 32} = 1.013$$

$$F_{\gamma d} = 1$$

Inclination factors calculation:
Since the load is perpendicular to the footing it means there is no inclination force.

$$F_{ci} = F_{qi} = F_{\gamma i} = 1$$

Substituting the obtained values into the Terzaghi's equation:
Then:

$$q_u = 20(3) * 32.67 * 1.031 * 1.016 * 1 + 0.5 * 20 * 30.22 * 3 * 0.98 * 1 * 1 = 2941.7\ kN/m^2$$

Taking the factor of safety as 3

$$q_{all} = \frac{qu}{FS} \qquad (14)$$

$$q_{all} = \frac{2941.7}{3} = 980.5\ kN/m^2$$

Raft Analysis

The reinforcement of the raft has been analyzed separately and due to the difference in load intensity in each raft panel, also the steel reinforcement of each raft is different from one another. The maximum load-bearing capacity of soil which was previously calculated as 980.5 kN/m^2 is given to the Tekla structural designer software. Moreover, we have assumed that the raft is fixed on four sides.

The thickness of the concrete raft remains the same as 3000 mm for the four side rafts and 4500mm for the central raft. However, due to the center raft of a much larger amount of steel, the raft thickness has been increased to 4500 mm.

The analysis of the Tekla structural designer shows that the raft will safely carry the load as shown in Figure 5.

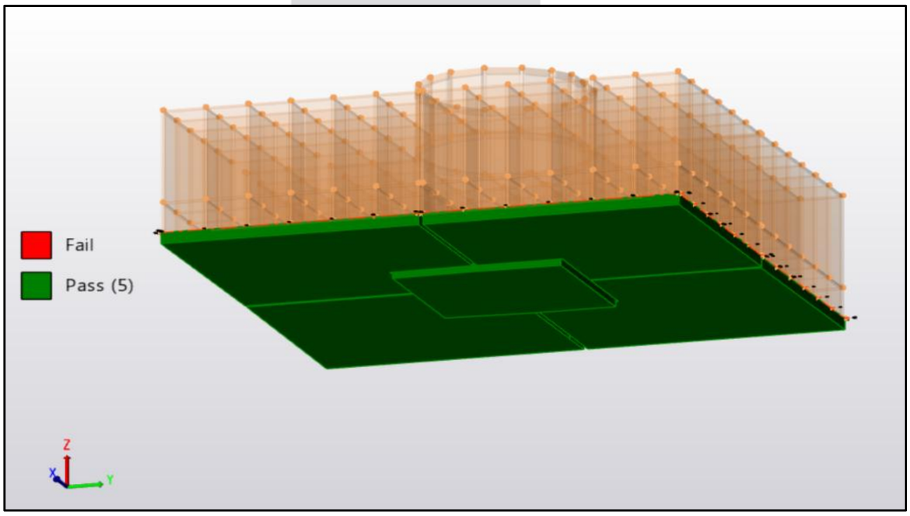

Figure 5: Raft Analysis Final Result

Reinforcement Arrangements

In the raft analysis, each section of the raft has been analyzed separately. The maximum stress on the top left side of the raft is calculated as 163.1 kN/m^2, where soil-bearing capacity which is 980 kN/m^2 can carry to imposed load.

The maximum stress load pressure of the top right of the raft is calculated as 181.1 kN/m^2. Moreover, for the bottom left section of the raft the maximum bearing stress load pressure is calculated as 135.8 kN/m^2. Also, for the bottom right raft the maximum stress load-bearing pressure is calculated as 154.5 kN/m^2.

The maximum load pressure occurs in the containment building due to the thickness of 1600mm of the containment wall. The maximum load pressure is calculated as 285 kN/m^2.

The location of each raft is shown in Figure 6 below.

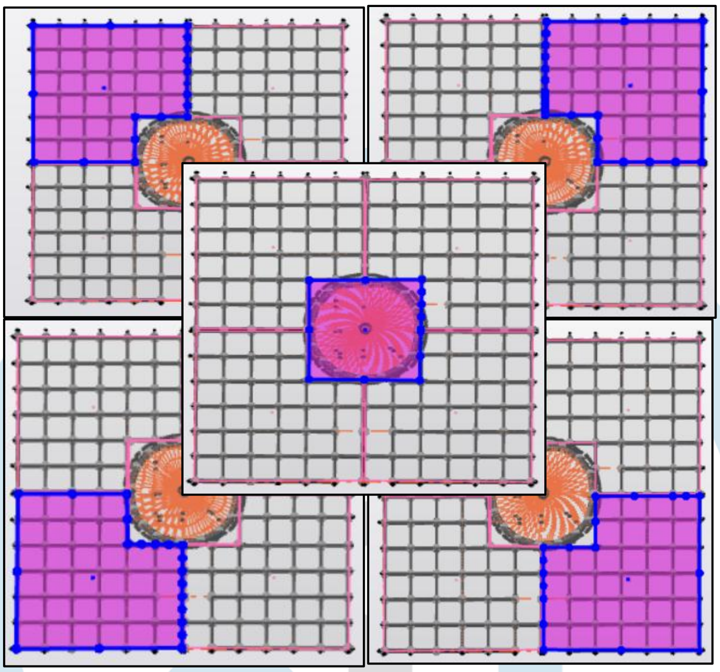

Figure 6: The Location of Each Raft

Table 1 shows the exact amount of steel reinforcement that has been used in each section of the raft.

Table 1 - Raft Steel Reinforcements Amount

Raft section	**Top X**	**Top Y**	**Botton X**	**Bottom Y**	**Total**	**Grand Total**
	mm²/m					
Top left	4676	4676	4676	4676	18704	174576
Top right	10500	10500	10500	10500	42000	
Bottom left	8042	8042	8042	8042	32168	
Bottom right	4676	4676	4676	4676	18704	
Central	15750	15750	15750	15750	63000	
Top left	4676	4676	4676	4676	18704	

Raft Deflection

Since the raft has been assumed to be fixed on four sides, the results show that the raft's movement in x-axes is zero. Figure 7 shows the displacement of raft in x-axis.

Finally, the result shows that the raft settlement in z-axes is 79.7 mm, where the maximum settlement occurs in the central section of the raft.

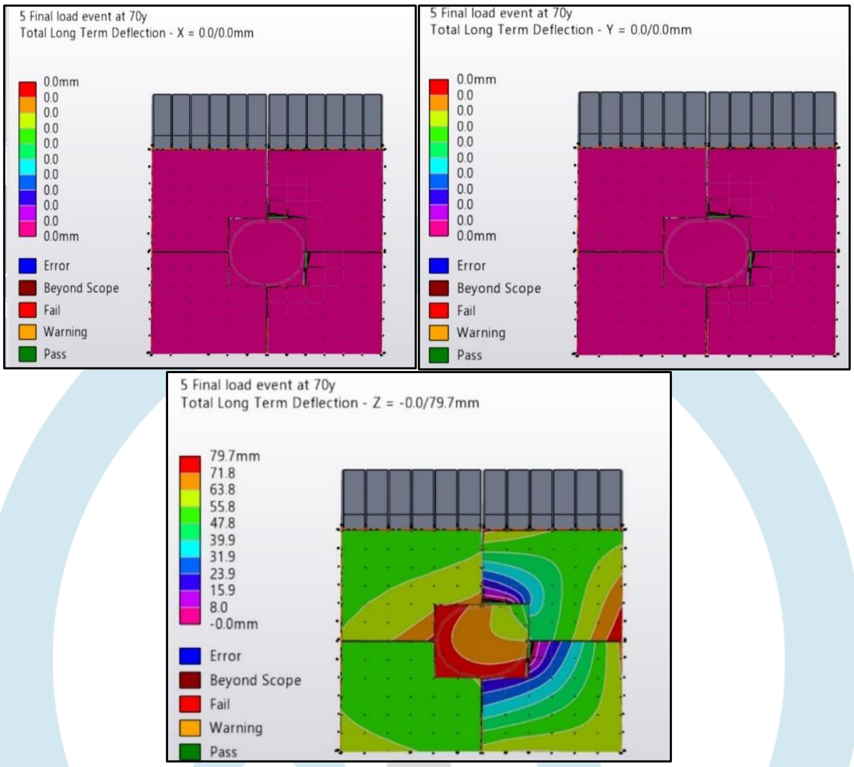

Figure 7: The Displacement of Raft in x-axis

To sum up, the maximum dead load in a column fund is to be around 26000 kN. Using the results from the Tekla Structural Designer program the maximum stress occurs in the contentment-building raft, where the result shows the stress to be 285 kN/m^2.

The thickness of the raft is considered to be 3000mm for four side rafts. However, the central raft where the contentment building located due to the requirement of a larger amount of steel the raft thickness is increased to 4500mm. To complete the analysis realistically it has been assumed that the water table to be in the depth of 12 meters. At the end of analysis, the pile bearing capacity was found as 26353.08 kN. The main rebars are considered to be 30mm with a distance of 200mm, in total 15 bars. To increase the shear resistance 16mm tie bar with a distance of 200mm is considered. In the design of the nuclear power plant, a total of 2880 piles with a diameter of 1m have been used to support the structural load.

The soil-bearing capacity of four layers was found to be 980.5 kN/m^2.

The Tekla Structural Designer analysis result shows that the raft only moves in the z-axes where the maximum settlement is found as 79.7 mm. Since the diameter of the raft is 4.5 meters and the settlement is only 79.7 mm, therefore it can be concluded that the raft has been designed withing the BS standards.

Finally, at the end of the analysis both raft and pile have been successfully designed.

IV. CONCLUSION

The construction of nuclear power plants is incredibly complex, and it requires a huge amount of investment to build. The plant is divided into many small and large buildings such as a reactor building (containment building), auxiliary building, fuel storage building, control room, administrative building, training building, etc. Among these buildings the containment building, and auxiliary building are the most important in a nuclear power plant where the containment building protects the outdoor environment from radiation and the auxiliary building is the main control building. In order to support the heavy load of both contentment and auxiliary buildings a combined pile raft foundation (CPRF) is designed. The use of a combined pile-raft foundation is recommended in many cases, however, due to the limited suitable site, the nuclear power stations are also built in soft soils.

Many researchers have designed a single foundation for contentment and auxiliary buildings. However, this will cause a problem, where if one side of the foundation is settled the adjacent building will also settle due to the expansion of concrete and steel and total load.

- In this study, the height of contentment building is taken as 47m, and the thickness of the wall is taken as 1.6 meters. The diameter of the contentment building is taken as 40 meters. As far as the auxiliary building is concerned, the length of the structure is taken as 121*121-meters. The exterior walls are taken as 600mm whereas the interior wall thickness is taken as 450mm. Moreover, initially, the thickness of the raft is taken as 3000mm for four side rafts. Due to the intensity of the load on the central raft, the thickness of the central raft increased to 4500mm.
- Conceptual modeling auxiliary building, and containment building of the plant using Tekla structural designer (Tekla, 2024).
    - The analysis result showed that the maximum axial load is calculated around 26000 kN and the bearing pressure on the raft is 284.7 kN/m^2.
    - The soil bearing capacity has been calculated at 980 kN/m^2. With the proper steel reinforcement of the raft using the Tekla Structural Designer software, all five rafts have successfully passed, and the results show that the load will be carried safely.
- Conceptual design of pile foundation using GEO5-Pile and GEO5-Slab.
    - The diameter of the pile is taken as 1 meter for both contentment and auxiliary buildings. The spacing of the pile in the contentment building is taken as 2.5 meters in both X and Y directions, with a total length of 20 meters.

The spacing of piles in the auxiliary building is taken as 5 meters in both X and Y directions, with a total length of 15 meters.

- It has been assumed that the GWT is located at a depth of 12 meters below the ground. The result shows that the bearing capacity is 26500 kN which is larger than the imposed load of 26000 kN.
- At the end of the analysis, it has been estimated that around 2880 piles will safely reduce the load due to the structure.

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