Analysis and Design of the Common Raft for a Chinese Third-Generation Nuclear Power Plant

Sun Xiaoying, Sui Ran, Meng Jian and Liu Yulin

Abstract This paper describes the analysis and design of the common raft for a Chinese third-generation nuclear power plant. The configuration of the common raft and the key methodologies involving in its analysis and design were studied. The general finite element software ANSYS was used to build the finite element model of nuclear island buildings, apply the loads on the model, and finally obtain the stress distribution and therefore the reinforcement requirement. During the process, transient temperature analysis method was adopted to get the temperature distribution in the common raft when accident condition happened. Instead of quasistatic method, the time history analysis method was employed in the stability analysis of the common raft. The common raft design was optimized by using the advanced techniques mentioned above.

Keywords Nuclear island building · Common raft · Finite element method · Time history analysis · Stability analysis

1 Introduction

The target nuclear power plant in this paper adopts china's advanced third-generation nuclear power technology. Provision of one common raft for nuclear island building is the characteristic of this third-generation technology. Because the reactor building, the safeguard building, the fuel building, and the electrical building (R-building, S-building, F-building, and E-building) shared one raft foundation, which is called common raft, the plane size of the common raft is very large (approximately 100 × 100 m). Furthermore, the thickness of common raft is not uniform and it varies in some local regions. The common raft has a complex geometry configuration, which leads into a complicated stress distribution in the transition zone between two buildings. The seismic responses of the buildings

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supported by the common raft are different and are not simultaneous. Thus, a more accurate method is required to evaluate the sliding forces and the overturning moments caused by loads from these buildings. In addition, the temperature distribution in the common raft is not linear under the accident condition. A transient temperature analysis method should be used to obtain an accurate temperature distribution to avoid an overconservative design. All these key aspects and methodologies were studied in this paper. The general finite element software ANSYS was used to analyze the stress distribution in the common raft to make sure that the design of the common raft is safe and economical.

## 2 Analysis and Design Process

2.1 Finite Element Model

#### 2.1.1 Finite Element Model of Common Raft

The reactor building, the safeguard building, the fuel building, and the electrical building of the nuclear island share one common raft whose plane size is about 100 × 100 m. Figure 1 shows the plan view of the common raft:

The average thickness of the common raft under the F-building, the E-building, and the S-building is 2.2 m, while the thickness under the R-building is 4.2 m. Additionally, the thickness above the gallery is 6.7 m. When modeling the common raft in ANSYS, different element types were chosen according to the different thickness requirements. The common raft portion having the thickness of 2.2 m was modeled by shell element using SHELL181, while the common raft portion thicker than 2.2 m was modeled by solid element using SOLSH190. Figure 2 shows the finite element model of the common raft:

The shell element and solid element were connected using a special shell element. The special shell elements shared the common nodes with solid elements,

Fig. 1 Plan view of the common raft
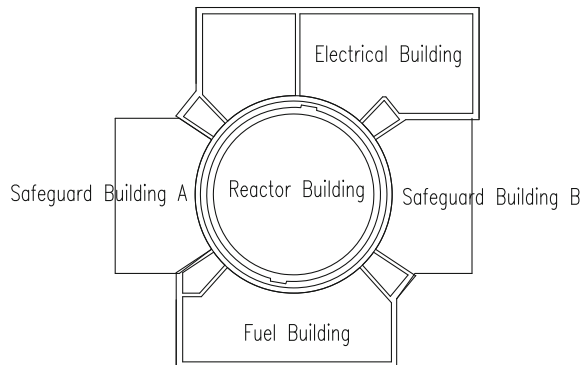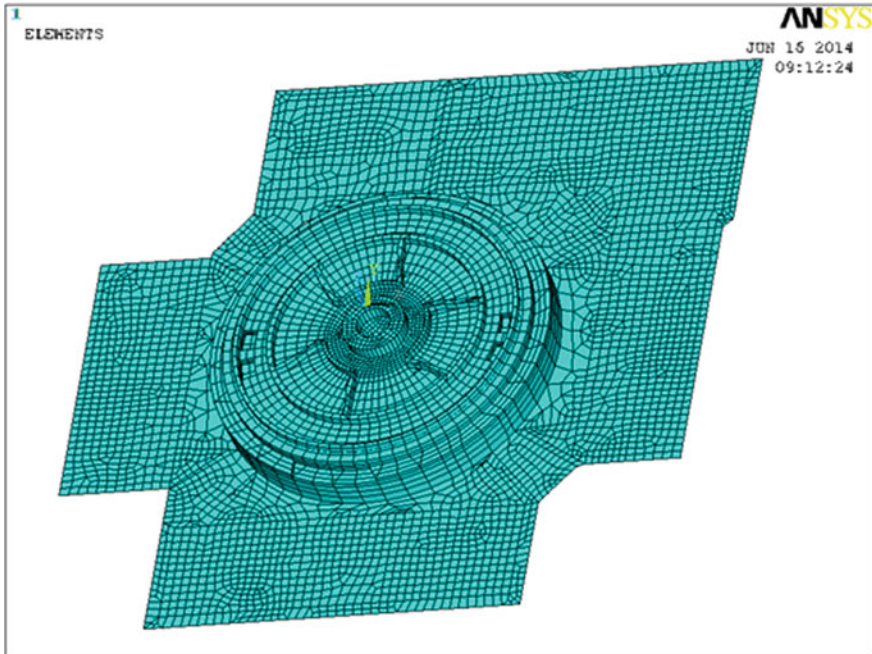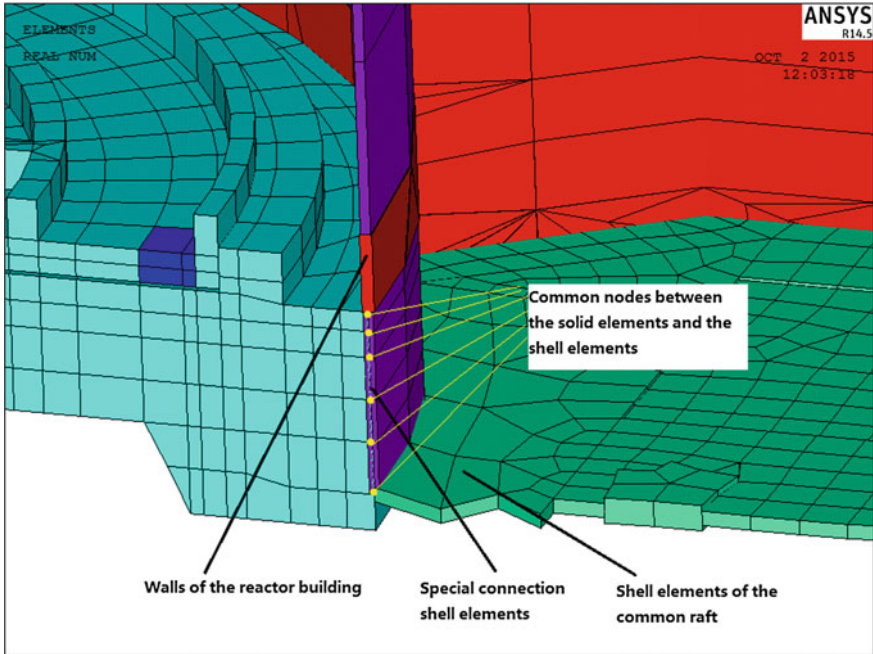
Fig. 2 Model of the common raft

having the same thickness with the elements of the adjacent walls but a very small density. The special shell elements also have the common nodes with the shell elements of the common raft. As shown in Fig. 3, the shell elements and the solid elements are connected well and the moment from the superstructures can be transferred to the common raft appropriately.

2.1.2 Models of Superstructures

The superstructures (R-building, S-building, F-building, and E-building) were modeled by shell elements according to its actual geometries and dimensions. It should be noted that only main structural members such as walls, slabs, and columns were modeled. The masses of equipment were considered as an equivalent density being added to the elements of local position. Figures 4 and 5 show the finite element models of the superstructures above the common raft.

2.1.3 Finite Element Model of Foundation

The soil elements were modeled by the group of spring elements under the common raft. The total stiffness of the foundation is calculated according to *Code for Seismic*

Fig. 3 Model of the common raft

Design of Nuclear Power Plants [1] and then distributed to each nodes of the common raft based on the specific principles. Each node has five spring elements (horizontal X-axis, horizontal Y-axis, vertical, rocking around X-axis, rocking around Y-axis). The collection of those springs can simulate the supporting of the soil foundation to the nuclear island buildings.

2.2   Stress Analysis and Reinforcement Calculation

2.2.1   Load and Member Forces

According to *Design Requirements for Prestressed Concrete Containment for Pressure Water Reactor Nuclear Power Plant* [2], the elementary loads considered in the common raft design are as follows:

(1)   D: permanent loads, including dead weight of structures, lateral earth pressure, hydrostatic pressure, equipment dead loads, effects of concrete creep, and shrinkage;

(2)   L: live loads, including live loads of movable equipment and other live loads (such as personnel weight, construction loads, polar crane loads);
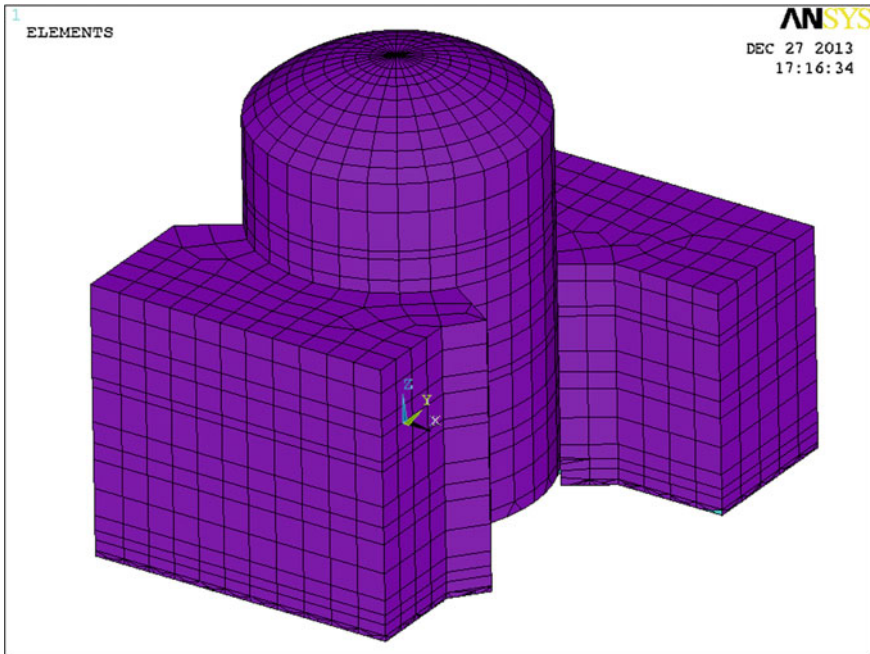
Fig. 4 Model of the reactor building

(3) T_0: thermal effects during normal operating or shutdown conditions;
(4) F: loads resulting from application of prestressing;
(5) P_a: pressure load generated by design basis accident;
(6) T_a: thermal effects generated by design basis accident;
(7) SL-1: operating basis earthquake; and
(8) SL-2: safe shutdown earthquake.

It should be noted that (1) transient temperature analysis method was used in present analysis to obtain accurate temperature distribution in the common raft to model rapid temperature increase and decrease when loss of coolant accident (LOCA) occurs; (2) the peak ground acceleration for E_2 is 0.3 g.

Totally eighteen load combinations were considered according to the code *Design Requirements for Prestressed Concrete Containment for Pressure Water Reactor Nuclear Power Plant* [2]. The member forces of the common raft (such as axial force, moment, shear force) for each load combination were calculated in ANSYS. Figure 6 shows only the member forces of the solid element of the common raft. The transverse axis in the Fig. 2.6a represents the radial distance between reactor core and the section under consideration. The longitudinal axis represents the value of the member forces. The curves with different colors represent the variation of the member forces. The indexes on the curves represent the load combination number.
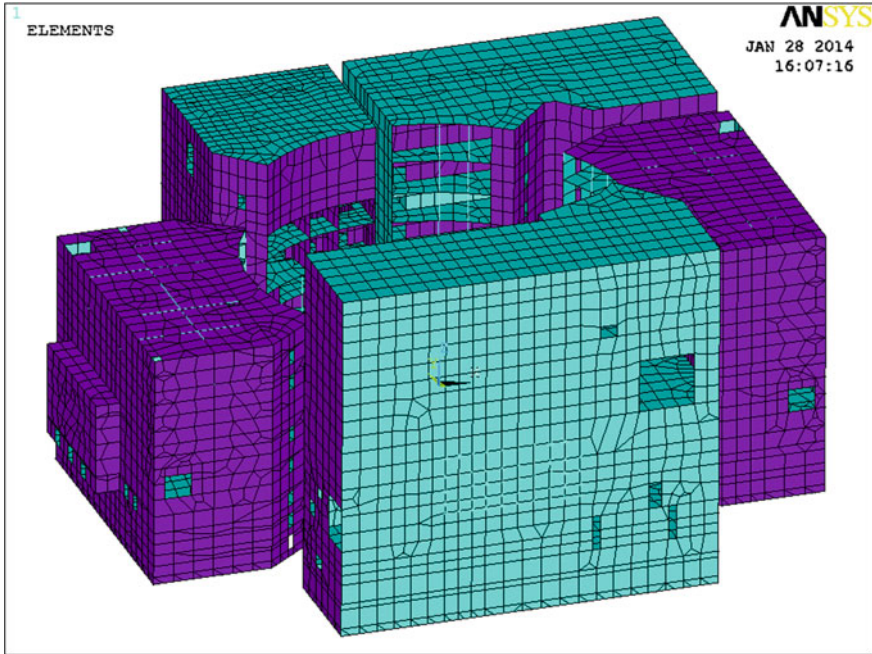
Fig. 5 Models of the S-building, E-building, and F-building

The member forces of the shell element of the common raft were not presented in this section because of the limited space.

2.2.2 Reinforcement Calculation and Layout

The required reinforcement including longitudinal reinforcement and shear reinforcement for each load combination is calculated according to *Design Requirements for Nuclear Safety Related Concrete Structure for Pressure Water Reactor Nuclear Power Plant* [3]. Figure 7 shows the reinforcement requirement of the common raft (solid element). As mentioned in Sect. 2.2.1, the transverse axis represents the radial distance between the reactor core and the section under consideration. The longitudinal axis represents the reinforcement amount. The curves with different colors represent the required reinforcement of the cross sections at different radii. The reinforcement amounts of the 18 load combinations were enveloped for the design of reinforcement.

Figure 8 shows the contour plan of the required reinforcement of the common raft (shell element). It should be noted that the required reinforcement was obtained by enveloping the required reinforcement of 18 load combinations. Different colors represent different reinforcement amounts that can be approximately estimated from the legend.
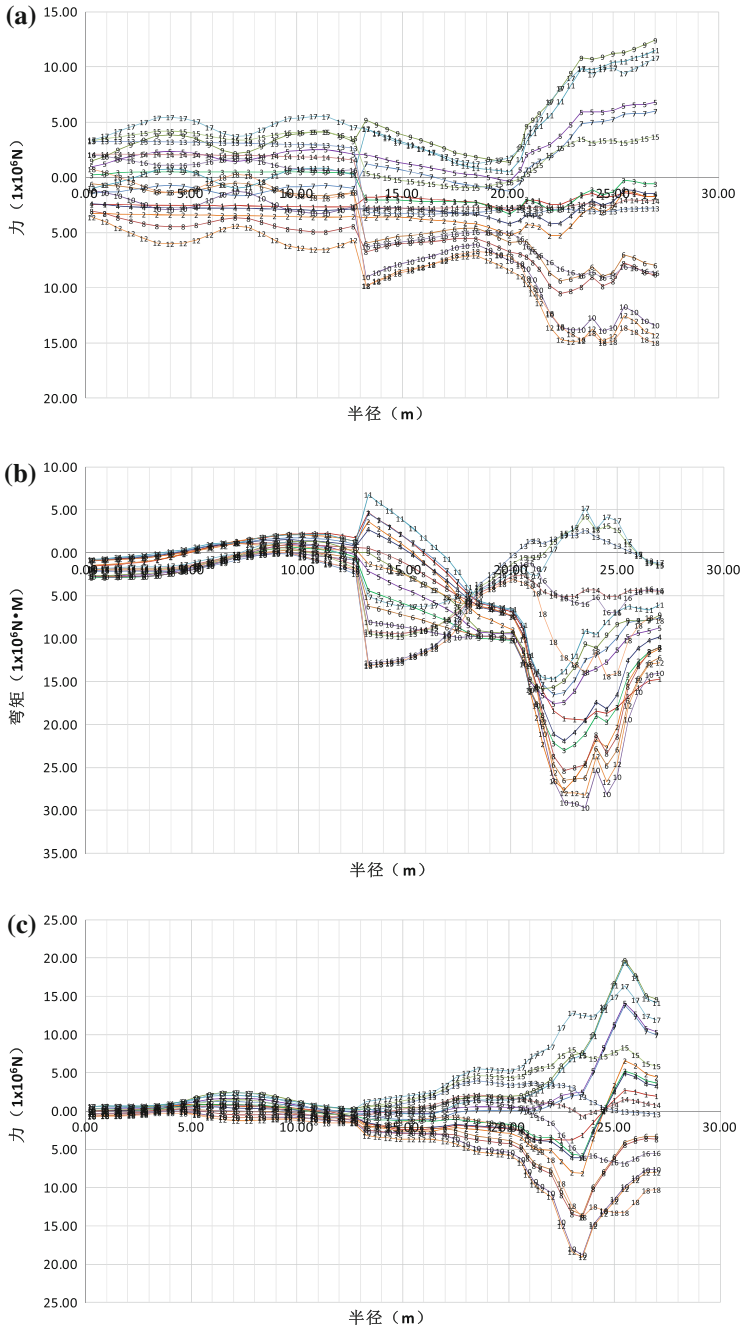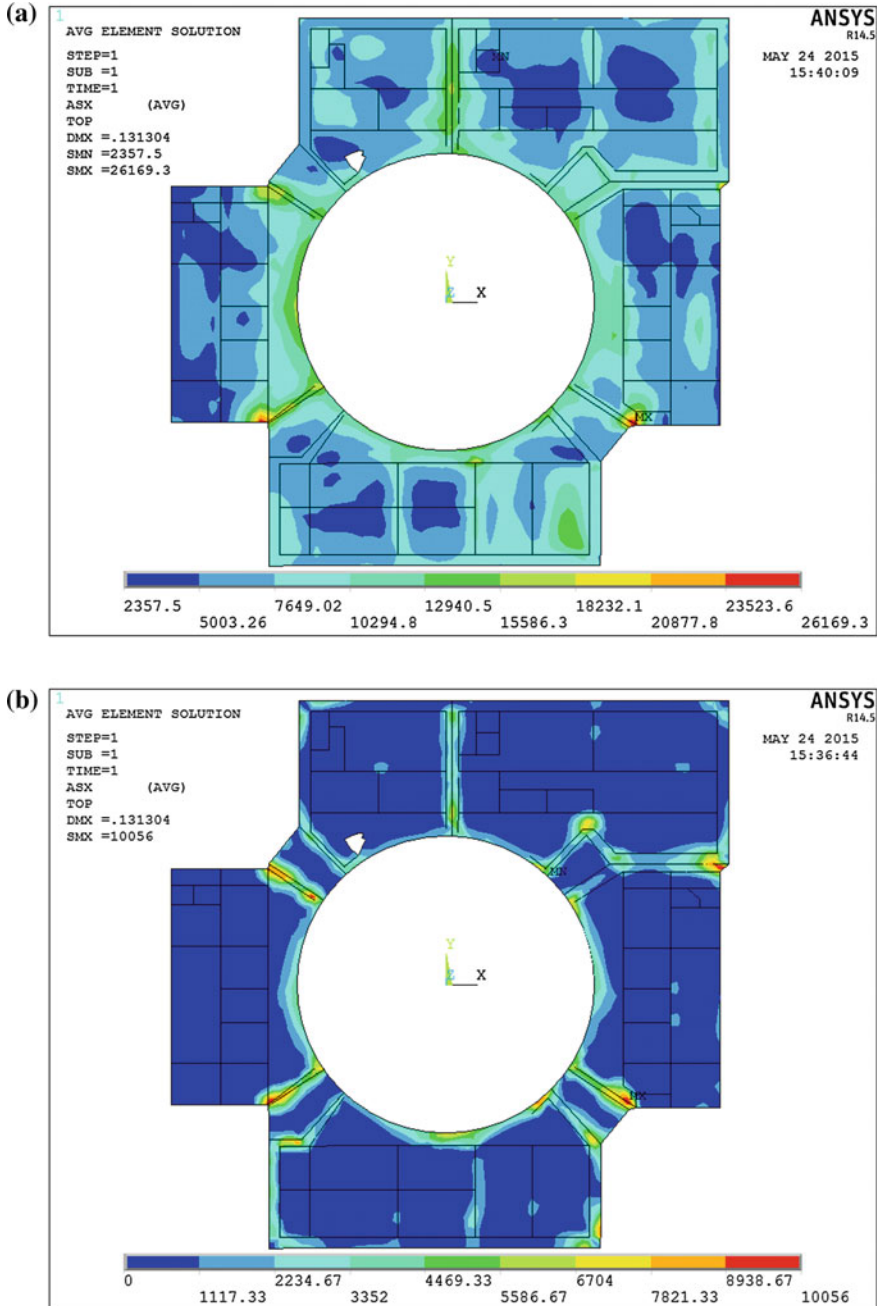
Fig. 6 Member forces of the common raft (*solid elements*) for different load combinations: **a** axial forces; **b** moment; **c** shear forces
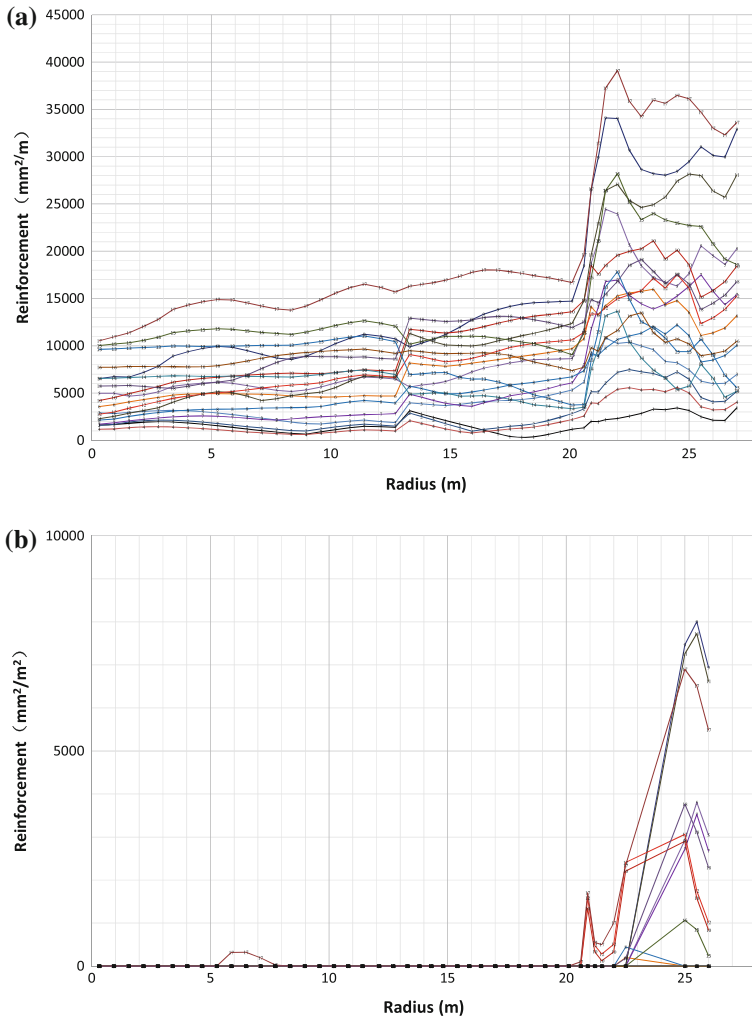
Fig. 7 Reinforcement requirement of the common raft (*solid elements*) for different load combinations: **a** longitudinal reinforcement; **b** shear reinforcement

Based on the enveloped reinforcement requirement and the configuration of the common raft, the reinforcement layout has been determined. Figure 9 shows only the reinforcement layout sketch in one location where the layout of the reinforcement is the most complicated. Reinforcement layout of other locations was not presented in this section because of limited space.

Fig. 8 Reinforcement requirement of the common raft (*shell elements*) for different load combinations: **a** longitudinal reinforcement; **b** shear reinforcement
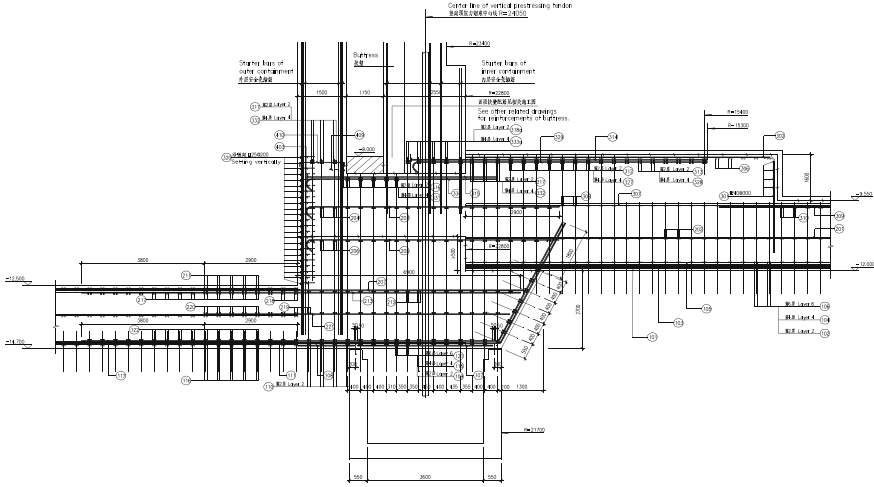
Fig. 9 Reinforcement layout sketch of the common raft

3 Stability Evaluation

The stability of the common raft was analyzed according to *Code for Seismic Design of Nuclear Power Plants* [1] and *Design code for nuclear safety related plants foundation for pressure water reactor nuclear power plants*. It should be noted that the partial factors of loads in load combination are 1.0 when evaluating the stability of the common raft.

3.1 Safety Against Sliding

According to *Code for Seismic Design of Nuclear Power Plants* [1] and *Design code for nuclear safety related plants foundation for pressure water reactor nuclear power plants* [4], the safety against sliding is calculated using the following formula:

$$\frac{E_r}{E_h} \geq K_h \tag{1}$$

where

E_r horizontal resistance acting on foundation (kN);
E_h sliding force acting on the common raft (kN);
K_h factor of safety against sliding, see *Code for Seismic Design of Nuclear Power Plants* [1].

Table 1 Factor of safety against sliding

SL-1	X-direction	E_r (10^5 kN)	20.08	
		E_h (10^5 kN)	5.26	
		E_r/E_h	3.81	
	Y-direction	E_r (10^5 kN)	21.79	
		E_h (10^5 kN)	6.93	
		E_r/E_h	3.144	
	Safety factor limit	K_h	1.5	
SL-2	X-direction	E_r (10^5kN)	16.27	
		E_h (10^5 kN)	13.61	
		E_r/E_h	1.2	
	Y-direction	E_r (10^5 kN)	20.98	
		E_h (10^5 kN)	18.21	
		E_r/E_h	1.15	
	Safety factor limit	K_h	1.1	

Time history analysis method was used to obtain accurate total sliding forces caused by loads of all superstructures above the common raft. The traditional quasistatic method assumes that the seismic response at different floor elevations occurs at the same time, and the response of different superstructures is simultaneous. By using time history method, the time histories of the sliding force for each building can be obtained and added to get the trend of total sliding force varied with time. It can also be found that when the maximum sliding force happens. By substituting the maximum sliding force and the horizontal resistance into formula (1), the minimum factor of safety against sliding can be calculated. Table 1 shows the evaluation results for the safety factor of common raft against sliding under SL-1 and SL-2 earthquakes.

3.2 Safety Against Overturning

According to *Code for Seismic Design of Nuclear Power Plants* [1] and *Design code for nuclear safety related plants foundation for pressure water reactor nuclear power plants* [4], the safety against overturning is calculated using following formula:

$$\frac{\sum M_r}{\sum M_q} > K_q \tag{2}$$

where

M_r moments resisting overturning (kN m) around X-axis or Y-axis, including resistance moment caused by gravity. The negative effect from upward vertical earthquake and buoyancy shall be considered;

Table 2 Factor of safety against overturning

SL-1	Around X-axis	$M_r(10^6$ kN-m)	224.96
		$M_q(10^6$ kN-m)	51.11
		M_r/M_q	4.4
	Around Y-axis	$M_r(10^6$ kN-m)	230.29
		$M_q(10^6$ kN-m)	43.6
		M_r/M_q	5.28
	Safety factor limit	K_q	1.5
SL-2	Around X-axis	$M_r(10^6$ kN-m)	224.96
		$M_q(10^6$ kN-m)	144.88
		M_r/M_q	1.56
	Around Y-axis	$M_r(10^6$ kN-m)	230.29
		$M_q(10^6$ kN-m)	118.17
		M_r/M_q	1.95
	Safety factor limit	K_q	1.1

M_q overturning moments (kN m) around X-axis or Y-axis due to horizontal earthquake and upward vertical earthquake;

K_q actor of safety against overturning, see *Code for Seismic Design of Nuclear Power Plants* [1].

Because of the same reason mentioned in Sect. 3.1, time history analysis method was also used here to obtain the time history of the total overturning moments caused by all the superstructures. By substituting the maximum total overturning moment and resisting moment into formula (2), the minimum factor of safety against overturning can be calculated. Table 2 shows the evaluation results of safety factors for the common raft against overturning under SL-1 and SL-2 earthquakes.

The results in Tables 1 and 2 shows that the factor of safety against overturning and sliding meets the design requirements. There is no underground water in the target nuclear power plant site; therefore, the floatation evaluation is not required to perform.

4   Conclusions

This paper mainly focused on the common raft analysis and design of a Chinese third-generation nuclear power plants. Using the general finite element software ANSYS, the stress distribution in the common raft and the required reinforcement were computed according to the Chinese national codes. The stability of the common raft was also evaluated.

The advance techniques were applied in the design of the common raft, which are as follows: (1) multitype finite element modeling method to make sure that the finite element model of the common raft is close to the actual structure; (2) transient

temperature analysis method to obtain accurate temperature distribution in the common raft under LOCA accident; and (3) time history analysis method to capture the variation of the total sliding force and overturning moment under earthquake to avoid an overconservative evaluation. All these techniques made the common raft design more safe and economical. The whole design methodology can be a reference to other third-generation nuclear power plants, which also adopt the common raft for the nuclear island buildings.

References

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Author Biography

Sun Xiaoying is working as senior engineer at Building Design Department of China Nuclear Power Engineering CO., Ltd. and mainly involves in the following: (1) application of advance techniques for the analysis and design of complex nuclear island structures; (2) fluid structure interaction analysis; and (3) seismic soil–structure interaction analysis.