Main Building of Conventional Island Performance Assessment Based on Different Methods of Elasto-Plastic Analysis

Lichao Shi, Zhicong Wang, Weichao Jia and Yankun Huang

Abstract After introduction of three different methods about elasto-plastic analysis, the analysis on main building of conventional island of nuclear power plant has been done, and the performance is evaluated under SL-2 earthquake action. The applicability of different methods on this kind of structural system is reviewed, so that it can be used accurately in the relevant engineering designs.

Keywords Main building of conventional island of nuclear power plant · Elasto-plastic analysis methods · Performance assessment

1 Introduction

Structural system of main building of conventional island is very complex. There are lots of equipment and piping layout. The distribution of story stiffness is uneven. The load is very big, and distribution is seriously uneven. Under the action of earthquake, the structure is extremely damaged seriously. In order to ensure the safety of nuclear island plant, main building of conventional island needs to maintain structural integrity under the ultimate safety ground of SL-2.

Based on performance of seismic design theory and difference of analytical methods, the performance of main building of conventional island of nuclear power plant is evaluated, and the applicability of different methods on this kind of structural system is reviewed.

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2 Analysis Methods

2.1 Simplified Analysis Method

For framed structures that do not exceed 12 stories in height and with no abrupt change of story stiffness as well as single-story factory buildings with reinforced concrete column, the simplified method in criterion may be used to check the performance characteristics of the structure under the rarely earthquake.

2.1.1 Basic Principle

This method is based on elasticity under rarely earthquake. Elasto-plastic response of the structure is obtained by proper modification. Simplified calculation formula is as follows:

$$\Delta u_p = \eta_p \Delta u_e = \mu \Delta u_y = \frac{\eta_p}{\xi_y} \Delta u_y \tag{1}$$

In the formula:

$\varDelta\mu_p$ elasto-plastic story drift
$\varDelta\mu_y$ yield story drift
$\varDelta\mu_e$ elastic story drift under the rarely earthquake
μ story ductility factor
ξ_y yield strength coefficient story
η_p amplifying factor for elasto-plastic story drift

2.1.2 Applicability of the Method

The performance of the structure under the rarely earthquake can be obtained by elastic calculation and appropriate correction. The method is simple and convenient, but it has certain applicability. For multi-story structures with a uniform distribution of story yield strength coefficient ξ_y or yield strength coefficient story ξ_y is not uniform distribution, but elastic stiffness along the height is relatively smooth, the simplified method is applicability.

2.2 Static Elasto-Plastic Analysis Method

Some form of horizontal load or lateral displacement along the height of the structure is applied, and the structure to displacement limits or formation collapse mechanism is pushed over, so as to understand elasto-plastic performance of the structure, and the weak part of the structure is evaluated.

2.2.1 Basic Principle

Some form of equivalent lateral force along the structural height to simulate earthquake is applied, and lateral force is gradually increased from small to large, gradually making the structure state elasto-plastic state from elastic state, eventually reach and exceed the prescribed elasto-plastic displacement.

The load–displacement curve is established under lateral load, and the structure performance point is obtained, and then, the structural performance evaluation is carried out.

2.2.2 Main Steps

(1) Transformation of capacity spectrum

With the increase in the lateral load, the relationship between the base shear and the peak displacement is obtained, which is the capacity curve (*Pushover curve*). The ability curve is converted to capacity spectrum curve, and each point needs to be converted. From any point of V_i, Δ_{roof} in the capacity curve converted to the corresponding capacity spectrum of S_{ai} and S_{di}; the conversion formula is as follows.

$$S_{ai} = \frac{V_i/G}{\alpha_1} \quad S_{di} = \Delta_{\text{roof}}/\gamma_1 X_{1,\text{roof}} \tag{2}$$

In the formula α_1 is mass participation factor of the first mode, γ_1 is participation factor of the first mode, $X_{1,\text{ roof}}$ is the peak amplitude of the first mode, S_{ai} is spectral acceleration and S_{di} is spectrum displacement.

Modal participation factor is defined as follows:

$$\begin{aligned} \alpha_1 &= \frac{\left[\sum_{i=1}^{N}(m_i\phi_{i1})\right]^2}{\left[\sum_{i=1}^{N} m_i\right]\left[\sum_{i=1}^{N}(m_i\phi_{i1}^2)\right]} \\ \gamma_m &= \frac{\sum_{i=1}^{N}(m_i\phi_{im})}{\sum_{i=1}^{N}(m_i\phi_{im}^2)} \end{aligned} \tag{3}$$

In the formula γ_m is participation factor of the m mode, m_i is the quality of i-layer, φ_{im} is the amplitude of m mode in i-layer and N is the number of layers.

(2) Demand spectrum conversion

According to the *ADRS* (acceleration–displacement response spectrum) format, the structure capacity curve and the demand spectrum are drawn using the coordinates of the acceleration response spectrum. By the standard acceleration response spectrum (S_a-T spectrum) converted to S_a and S_d spectrum (spectral acceleration for the vertical coordinates, spectral displacement for the horizontal coordinates), is the

ADRS spectrum. The first point on the response spectrum curve has certainly a relationship with spectral acceleration S_a, velocity spectrum S_v, spectrum displacement S_d and period T. By the standard acceleration response spectrum (S_a-T spectrum) mode converted to *ADRS* mode, it is must to determine every point value of S_{di} corresponding to the value of S_{ai} and T_i on curve. The relationship can be derived from the following formula:

$$S_{di} = \frac{T_i^2}{4\pi^2} S_{ai} g \tag{4}$$

The standard demand response spectrum contains a constant acceleration spectrum and a constant velocity spectrum, which have the following relations at the period T_i:

$$S_{ai} g = \frac{2\pi}{T_i} S_v \quad S_{di} = \frac{T_i}{2\pi} S_v \tag{5}$$

(3) Determine performance points

Use double lines to represent the capacity spectrum. The area under the capacity spectrum and the double line representation area are equal. If the reduced demand spectrum and capacity spectrum intersect at point (S_{api}, S_{dpi}) or intersect at the range of 5% of S_{dpi}, then the intersection point is the performance point; if the intersection is not in the allowed range, the calculation process should be repeated until it is satisfied.

(4) Seismic performance evaluation

Through the following two aspects, the structural seismic performance is evaluated: (1) story drift: whether the limit value of elastic story drift in seismic code can be satisfied; (2) structure deformation: using to plastic hinge distribution, the weak position of the structure is determined. According to the state of plastic hinge, whether the structural member can satisfy the seismic performance level under the specified earthquake action is determined.

2.2.3 Applicability of the Method

The basic assumption of the method of static elasto-plastic analysis:

(1) The response of the structure is related to the freedom system of equivalent single degree, that is, the structural response is controlled by the first mode of the structure;
(2) The deformation along the height of the structure is expressed by the mode of the vibration type, that is, in the whole seismic response, the inertia force remains the same as the structure mass distribution or the mode of vibration.

From above basic assumptions, we can see that the static elasto-plastic analysis has is applicability and limitations. Related research results show that the structure which 1 and 2 cycles is given priority to translation and the height is not more than 150 m; this method can accurately analyze the seismic reaction of the structure.

2.3 Dynamic Elasto-Plastic Analysis Method

Because of nonlinear properties of the structure, the building is considered an elasto-plastic vibration system. Earthquake ground motion displacement, velocity and acceleration brought by natural or artificial earthquake wave act on the structure. In order to obtain instantaneous displacement, velocity and acceleration, research dynamic response, damage mode and weak links etc. in the earthquake, finally evaluate seismic performance of the structure, dynamic equation is calculated by step-by-step integration method.

2.3.1 Basic Principle

Numerical method is used to solve nonlinear motion equation of $\mathrm{M}\ddot{\mathrm{u}}_t + \mathrm{C}\dot{\mathrm{u}}_t + \mathrm{Ku}_t = \mathrm{F}_t$. Calculating the response of displacement, velocity and acceleration of the structure under earthquake at any moment obtains the process of elastic and elasto-plastic stage internal force change and the bearing force change of the structure under earthquake action.

The dynamic response of the structure is analyzed, which can be divided into several small time periods, and the numerical solution is obtained by the numerical integration of the dynamic equation. As the structural stiffness recovery degree will constantly change according to the size of the structural response, each step of the analysis must be based on structure response status, to determine the stiffness of the structure, and then, the next step of calculation can be done.

2.3.2 Main Considerations

(1) Choosing of earthquake wave

The correct choice of seismic acceleration time history curve needs to consider three factors: frequency spectrum characteristic, effective peak value segment and duration. Frequency spectrum characteristic can be characterized with the seismic influence coefficient curve, which is based on the category of the site and the design earthquake grouping. The effective duration of time history curve of the earthquake wave is general from the first time to reach the point which is the 10% of the maximum peak, until reaching the last point which is the 10% of the maximum peak. Generally speaking, the effective duration is 5–l0 times of the structure period, that is, the displacement of the structure vertex can be repeated 5–10 times according to the basic cycle.

(2) Material model

The restoring force model of the material is mainly composed of two parts, the first is the skeleton curve and the second is the hysteresis curve with different characteristics. The skeleton curve refers to the connection of the peak points of the hysteresis curve. Experiments show that the connection of the peak points is very close to the force–deformation curve when the load is monotonic. Hysteresis curve shows the plastic properties of the component. The area enclosed by hysteresis loop represents the energy dissipation capacity of component.

(3) Unit model

The applicable unit model is selected according to different computing software. One-dimensional elasto-plastic units (beams and columns) mainly include fiber bundle model and plastic hinge model; two-dimensional elasto-plastic element (shear wall, floor) mainly include fiber beam model, the shell element injury model, elasto-plastic of wall element model and the multilayer shell model, etc.

(4) Result output and judgment

After elasto-plastic analysis, the results in several aspects are needed to see: the consistency of the elasto-plastic model and the elastic model, the total shear force, displacement and deformation, and the evaluation of the performance of the components.

2.3.3 Applicability of the Method

The premise and the assumption of the method are relatively few, and the applicability is strong. It is the most direct and accurate method to evaluate the seismic performance of structures.

3 Engineering Example

Taking a project as an example, the performance of the main power house under earthquake action of SL-2 is assessed and compared.

The span of turbine generator building is 42.5 m. Column spacing is of four kinds as 8, 10, 12 and 13 m. The roof of turbine generator building is composed of pitched steel roof trusses. Steel beam is layout on steel roof truss, and in situ reinforced concrete slabs formed on profiled steel sheets are placed on steel secondary beam. The main structure floors of turbine generator building are: bottom layer (−12.00 m), middle layer (±0.00 m), operation floor (9.25 m) and roof; Seismic fortification intensity is 7°.

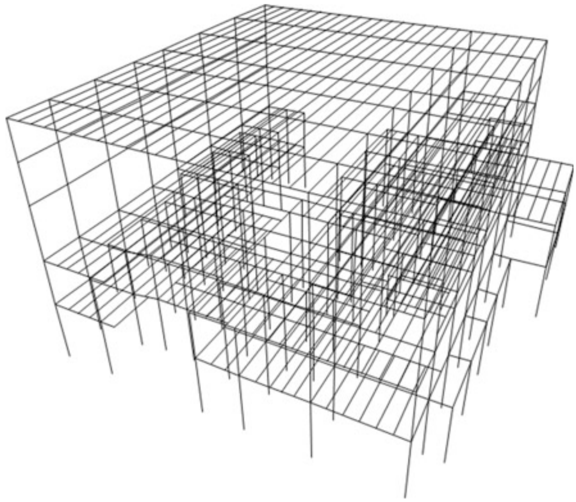

Fig. 1 3D finite element model

Structural system of main building is complex, and the vertical stiffness variation is large. The performance reaction of the structure under earthquake action of SL-2 is needed to be obtained. So the simplified method in criterion does not apply. Static elasto-plastic and dynamic elasto-plastic analysis methods are used to analyze, and the results are compared.

3.1 Model Building

The 3D finite element analysis model is established according to the design drawing, the load distribution map and the simplified principle. At the same time, the plastic behavior of the structural unit is specified. The beam and column element adopt the plastic hinge element, and the wall adopts the layered shell element as shown in Fig. 1.

3.2 Seismic Performance Evaluation of Structure

3.2.1 Story Drift

(1) Static elasto-plastic analysis method

By calculating two loading mode of the uniform load and modal load, in *X* direction the maximum story drift that occurred on the second floor is 1/84; in *Y* direction the maximum story drift that occurred on the fifth floor is 1/81.

(2) Dynamic elasto-plastic analysis method

Acceleration history data which are obtained from Seismological Bureau are used to obtain dynamic elasto-plastic time history analysis. In *X* direction, the maximum story drift that occurred on the fourth floor is 1/185; in *Y* direction, the maximum story drift that occurred on the fifth floor is 1/191.

(3) It can be seen from the story drift that the results of the two methods are basically consistent. The story drift of static elasto-plastic analysis method is bigger than the story drift of dynamic elasto-plastic analysis method, because static elasto-plastic analysis method uses spectrum, and dynamic elasto-plastic analysis method only uses a specific time history curve.

3.2.2 Hinge Case

Under the earthquake of SL-2, the results of hinge case by using the two analysis methods are basically consistent. The end of beams appears as plastic hinge basically, and many ends of column appear as plastic hinge. Part of the plastic hinge enters into the stage of life safety (LS), but do not enter into the stage of collapse prevention (CP) as shown in Figs. 2 and 3.

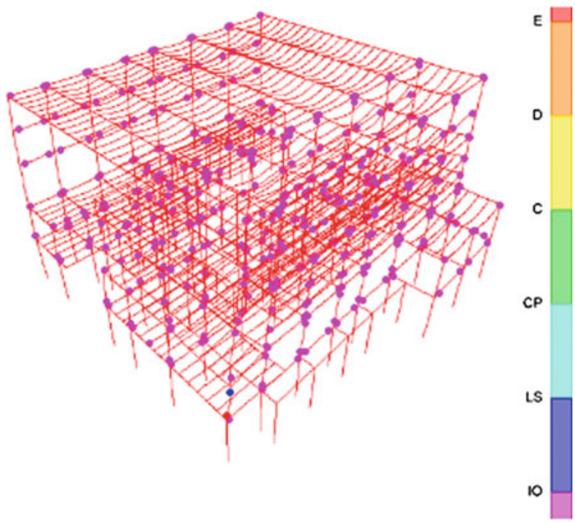

Fig. 2 Hinges under earthquake in *X* direction

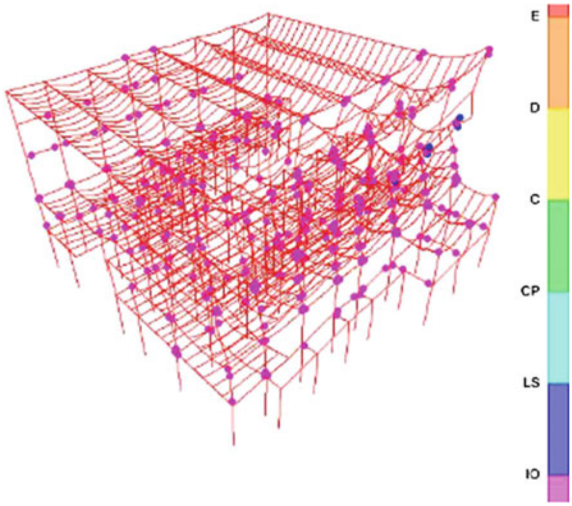

Fig. 3 Hinges under earthquake in *Y* direction

4 Conclusions

(1) The simplified method is not suitable for performance evaluation of main building of conventional island under the earthquake of SL-2.
(2) Static elasto-plastic analysis method and dynamic elasto-plastic analysis method are both suitable for performance evaluation of main building of conventional island under the earthquake of SL-2. The trend of the results of the two methods is basically consistent.
(3) The static elasto-plastic analysis method is based on the spectrum, and the dynamic elasto-plastic analysis method is based on the specific time history curve, so the static elasto-plastic analysis method is more conservative than the dynamic elasto-plastic analysis method.

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