Nonlinear seismic responses of the soft rock site for nuclear power plants

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Abstract. With the development of the nuclear power industry, high-quality bedrock nuclear power stations have become scarce. Thus, it is inevitable that nuclear power stations will be built on soft rock sites. This involves the issue of the seismic safety of soft rocks as sites for nuclear power plants. Based on the soft rock site involved in the site selection for nuclear power plants, this paper uses ground motions with different spectral characteristics. Using the DEEPSOIL software for soil layer analysis and the Abaqus finite element software, one-dimensional equivalent linear and nonlinear methods are employed to compare and analyze the characteristics of the nonlinear seismic response of the soft rock site for nuclear power plants. The soft rock site has a significant amplification effect on the input ground motion. The equivalent linear and nonlinear methods have different levels of influence on the acceleration response of the soft rock site. Under the action of far-field earthquakes, surface acceleration and its response spectrum, which were calculated using the abovementioned methods, are relatively close. As the input ground motion intensity increases, the nonlinearity of the soft rock increases, and the amplification effect of the soft rock site weakens. However, the peak ground acceleration of the surface obtained using the two methods gradually differs. Moreover, the nonlinearity is greater than the equivalent linear. Therefore, the nonlinear characteristics of soft rocks should be considered in the site selection and seismic analysis of nuclear power plants.

1. Introduction
Analysis of the site seismic response is important in the estimation of earthquake damage and in seismic engineering. Moreover, it plays a significant role in the seismic safety evaluation of various engineering sites. In view of this, the selection of site analysis method has become a hotspot research topic. Currently, the methods for analyzing the effect of soil layers on seismic waves mainly include the equivalent linear and nonlinear methods. The equivalent linear method is widely used owing to its simple principle, easy-to-obtain parameters, and small amount of calculation. However, it cannot truly reflect the dynamic nonlinear characteristics of the soil, especially under the action of strong ground motion. Conversely, the equivalent nonlinear method is an analytical method for the seismic responses of soil layers based on the nonlinear constitutive model of soil dynamics. Compared with the equivalent linear method, this method is more complicated, as it needs to consider the nonlinear characteristics of the soil under the action of
earthquake. Therefore, the nonlinear method can more realistically reflect seismic wave propagation in soil layers. Scholars at home and abroad have conducted in-depth research on site seismic actions using both the equivalent linear and nonlinear methods. Specifically, Robert et al., Youssef et al., and Kausel et al. found that, when the input ground motion intensity was relatively large, the equivalent linear method would overestimate the soil’s ability to dissipate energy [1-3] while ignoring numerous high-frequency components. Li et al. used the equivalent linear method to analyze the site seismic effect under the action of strong ground motion, which basically reflected the significant influence of the nonlinear characteristics of the soil on the characteristics of ground motion [4]. Bo et al. stated that the result of the site seismic effect calculated using the equivalent linear method was greater than that of the actual situation. Thus, further examination of the effect of the nonlinear characteristics of the soil on the ground motion would be necessary [5]. With regard to the nonlinear method, Martin et al. proposed the Davidenkov model of the $G/G_{\text{max}}\gamma$ curve [6]. Unfortunately, when the shear strain is infinite, the shear stress of this model would also become infinite, which is inconsistent with the actual situation of the soil layer. Therefore, using the segment function method, Chen and Zhuang further modified its skeleton curve [7]. Dong et al. studied the site seismic effect in the Quanzhou Basin using the one-dimensional equivalent linear method and the two-dimensional nonlinear method, mainly considering the effect of terrain fluctuation and lateral unevenness on the ground motion [8]. It can be inferred that the literature above is largely based on the examination of the seismic responses of soil layers while the number of selected ground motions is limited and unrepresentative. Moreover, the site seismic responses under special structures have been rarely taken into consideration.

With the rapid development of nuclear power projects, high-quality bedrock sites for nuclear power plants have become scarce. Thus, soft rock sites and soil sites will be eventually used for the construction of nuclear power plants, which will surely give rise to higher technical requirements for seismic safety. Therefore, in this paper, we established analytical models using both the equivalent linear and nonlinear methods to describe the nonlinear dynamic stress–strain relationship between a soft rock site and the ground motions of different spectral characteristics. For this, the DEEPSOIL software for soil analysis and the Abaqus finite element software were used. Then, we conducted comparative analysis on the seismic responses of the soft rock site between the two methods to provide a reference for site selection and seismic design of nuclear power plants.

2. Overview of the soft rock site and input ground motion

2.1. Overview of the soft rock site

The target site of the nuclear power plant is a soft rock site. The upper part of its soil layer is classified as the Quaternary Holocene intercontinental sedimentary layer; the soil is mainly composed of silty clay with a part of silty sand and silty soil locally, and the exposed thickness is 8.0–25.5 m. The lower part of the cover layer is composed of strongly weathered mudstone, moderately weathered mudstone, and sandstone, which are continuously distributed and exhibiting an obvious characteristic of horizontal stratification. As a typical soft rock site, it is considered as a good-quality site for nuclear power plants. According to the existing borehole data, one section of the site was selected for analysis; the horizontal span of this section is 9.35 km, including four boreholes. Table 1 presents the specific soil layer information.

| Soil lithology                  | Thickness (m) | Unit weight $\gamma$ (kN/m$^3$) | $V_s$ (m/s) | Thickness $s$ (m) | Unit weight $\gamma$ (kN/m$^3$) | $V_s$ (m/s) |
|--------------------------------|---------------|---------------------------------|-------------|-------------------|---------------------------------|-------------|
| Silty clay                     | 8.5           | 19.8                            | 291         | 10.2              | 19.6                            | 316         |
| Strongly weathered mudstone    | 9.7           | 20.5                            | 435         | 9.4               | 21.1                            | 461         |
| Moderately weathered mudstone  | 17.3          | 22.3                            | 593         | 13.9              | 22.5                            | 559         |
| Sandstone                      | 14.5          | 22.8                            | 826         | 16.5              | 23.0                            | 807         |

Table 1. Borehole soil layer information of the soft rock site
### 2.2. Input ground motion

The near-field MZQP wave from China and the far-field SUCHIL wave from Mexico were chosen as the input bedrock ground motions for analysis (Table 2). The peak ground acceleration (PGA) of the bedrock ground motion was adjusted to 0.05, 0.10, and 0.20 g to examine the impact of minor earthquakes, moderate earthquakes, and strong earthquakes, respectively. Figure 1 presents the acceleration time history and Fourier spectrum recorded in the original ground motion data.

| Ground motion information | MZQP wave | SUCHIL wave |
|----------------------------|-----------|-------------|
| Earthquake place          | Wenchan, China | Michoacan, Mexico |
| Event time (yy/mm/dd/hh:mm) | 2008/05/12/14:28 | 1985/09/19/07:19 |
| Moment magnitude           | 8.0       | 8.1         |
| Fault distance (km)        | 2.0       | 226.4       |
| Station code               | 51MZQ     | SUCHIL      |
| Selected horizontal component | EW       | NS          |
| Sampling rate (Hz)         | 200       | 100         |
| Horizontal PGA (g)         | 0.841     | 0.078       |
| Predominant period (s)     | 0.10      | 0.35        |
| Arias intensity (m/s)      | 11.622    | 0.0657      |
| Significant duration D₅₀₉₅ (s) | 30.065 | 20.48 |

![Figure 1. Original acceleration time history and Fourier spectrum of the input ground motions](image)

### 3. Site seismic effect calculation model

#### 3.1. Equivalent linear model
The basic concept of the equivalent linear method is to use an equivalent steady-state regression curve to approximately represent the average relationship of all regressions on the basis of dynamic equivalent linearity, where the strain amplitude of the steady-state regression curve is the equivalent strain amplitude. Then, the equivalent shear modulus and equivalent damping ratio are adopted to replace the nonlinear shear modulus and damping ratio of the soil, so that a nonlinear problem can be converted into a linear problem.

The actual stress–strain relationship of the soil can be expressed by the equivalent shear modulus and equivalent viscous damping ratio. The equivalent damping ratio is proportional to the energy dissipation in a period, which can be obtained by solving the area of the hysteresis loop as follows:

$$\phi = \frac{\Delta W}{2\pi G \gamma_c^2}$$

where $\phi$ denotes the equivalent damping ratio, $\Delta W$ denotes the area of the hysteresis loop, and $\gamma_c$ denotes the shear strain amplitude of the hysteresis loop.

Figure 2 presents the relationship curves of the dynamic shear modulus ratio $G/G_{\text{max}}$, the dynamic damping ratio $\lambda$, and the dynamic shear strain amplitude $\gamma$ for various soil types, from which the parameters of each soil layer can be determined.

![Figure 2. Relationship among the $G/G_{\text{max}}$, $\lambda$, and $\gamma$ of the soil](image)

In the DEEPSOIL software, the frequency domain analysis method was used for the analysis of the equivalent linear seismic effect of the soil. The principle of this method is as follows. Considering that the soil acts on the uniform elastic semi-infinite space bedrock, by dispersing the soil into multiple layers (the bottom layer is the bedrock), the soil layer displacement can be obtained by solving the one-dimensional wave equation.

3.2. Nonlinear model

A modified Davidenkov dynamic viscoelastic–plastic model was utilized to describe the dynamic nonlinear characteristics of the soil. Moreover, a soft rock site calculation model was established using the Abaqus finite element software [9]. Subsequently, through the UMAT–VU-MAT interface of the Abaqus software, FORTRAN was embedded to create subroutines for the dynamic constitutive relationship of the soil. To ensure accurate calculation and to reduce the calculation time as much as possible, we mainly used quadrilateral elements when drawing the grid of the finite element model, supplemented by a few triangular elements. The ground motion energy was transmitted to the far-field site, and the scattered waves propagating outward were required to have no or almost no reflection at the boundary of the finite area intercepted by the calculation. Therefore, vertical restraints were set on both sides of the calculation area of the soil layer, whereas viscous damping and artificial boundary of the linear spring were applied in the horizontal direction [10].

4. Calculation results and analysis

4.1. Amplification factor of ground acceleration
By comparing the amplification factors of the PGA of the soft rock site obtained using the one-dimensional equivalent linear method and the two-dimensional nonlinear method, the results presented in Figure 3 were obtained. From the figure, it can be seen that the equivalent linear and nonlinear methods exhibit different degrees of amplification on the acceleration response of the soft rock site. Specifically, the following characteristics are present:

1. There is no specific size relationship between the PGA values obtained using the equivalent linear and nonlinear methods. The effects of PGA amplification derived by both methods exhibit a decreasing trend with the increase in the input ground motion intensity of the bedrock. Specifically, the ratios of the PGA amplification factor between moderate and minor earthquakes, and between strong and minor earthquakes, are 0.82–0.90 and 0.69–0.76, respectively, for the near-field MZQP wave, and 0.79–0.87 and 0.64–0.72, respectively, for the far-field SUCHIL wave.

2. The PGA amplification factor obtained using the equivalent nonlinear method is significantly greater than that obtained using the equivalent linear analysis. This is mainly because the seismic wave would experience multiple refractions or reflections after being input into the bedrock, which would intensify the PGA amplification effect at the boreholes. Thus, it can be inferred that nonlinear analysis is capable of truly reflecting the propagation characteristics of complex ground motions, whereas the conventional equivalent linear analysis method cannot fully reflect the effect of soft rock site conditions on the ground motion effect.

3. The difference between the PGA amplification factors obtained using the two different analysis methods increases as the input ground motion intensity increases. When the input ground motion intensity increases, the soil exhibits a more significant nonlinear effect. Because the equivalent linear method cannot fully reflect this characteristic, the difference between the results obtained using the two analysis methods increases. Meanwhile, the difference is more significant under the action of near-field ground motion and less significant under the action of far-field ground motion.

\[ \text{Figure 3. Comparison of the PGA amplification factor} \]

**4.2. Spectral characteristics of ground motion responses**

To compare the difference between the spectral characteristics of the ground acceleration responses derived by the one-dimensional equivalent linear method and the two-dimensional nonlinear method, Figure 4 compares the ground acceleration response spectrum at the representative borehole ZK1 under the action of strong earthquakes. The figure indicates that the ground acceleration response spectrum shifts toward the long-period direction under the action of near-field ground motion, and the PGA of the response spectrum significantly increases. The PGA of the response spectrum obtained using the nonlinear method is slightly larger than that obtained using the equivalent linear method. Under the action of far-field ground motion, the ground acceleration response spectrum shifts slightly toward the short-period direction, and the PGA of the response
The PGA values of the response spectrum obtained using the two methods have no significant difference. The response spectrum indicates that the amplification effect of the one-dimensional equivalent linear method on the long-period ground motion is not reflected; the aggregation effect of the two-dimensional nonlinear method that may be caused by the lateral unevenness of the soil layer and the strong nonlinearity of the soil is also not reflected.

Figure 4. Comparison of the ground acceleration response spectrum under strong earthquake (ZK1)

4.3. Change in peak ground acceleration along the depth direction

To elaborate the difference between the changes in PGA values along the soil depth direction obtained using the one-dimensional equivalent linear method and the two-dimensional nonlinear method, Figure 5 presents the comparison of the PGA developing trend of a representative borehole (ZK1) along the soil depth direction under the action of a strong earthquake. From the figure, it can be seen that the acceleration amplification factor obtained using the nonlinear method is slightly larger than that obtained using the equivalent linear method. As the input PGA increases, the nonlinearity of the soft rock site gradually increases, whereas the amplification effect weakens and the acceleration amplification factor gradually decreases. The PGA values of the soft rock site obtained using the equivalent linear and nonlinear methods both exhibit a monotonic increasing trend with the change in soil depth. The PGA only decreases at certain depths. Overall, the PGA obtained using the nonlinear method is greater than that obtained using the equivalent linear method. However, the equivalent linear wave transmission method treats the borehole as a “soil strip structure” and cannot reflect the influence of the bedrock or ground surface undulation, as well as the effect of uneven distribution of the soil layer on the seismic effect.
Figure 5. Comparison of the developing trend of the PGA amplification factor along the soil depth direction at a representative borehole (ZK1)

5. Conclusions

Using the soft rock site of a certain nuclear power plant as the research object, this study adopted both the one-dimensional equivalent linear method and the two-dimensional nonlinear method to describe the nonlinear dynamic stress–strain relationship of the soft rock site by using the DEEPSOIL software for soil analysis and the Abaqus finite element software. Based on the near-field MZQP wave and the far-field SUCHIL wave, we compared and analyzed the nonlinear seismic response characteristics of the soft rock site and obtained the following conclusions:

(1) The soft rock site has a significant amplification effect on the input ground motion. The equivalent linear and nonlinear methods have different effects on the acceleration response of the soft rock site. Specifically, the ground acceleration amplification is more significant under the action of near-field ground motion.

(2) The PGA of the response spectrum is significantly greater than that of the bedrock spectrum, and the response spectrum shifts toward the long-period direction under the action of near-field ground motion and toward the short-period direction under the action of far-field ground motion. Under the action of far-field ground motion, the ground acceleration and the corresponding response spectrum calculated using the two methods are similar.

(3) For the acceleration response of the soft rock site, the characteristic of nonlinearity is overall more significant than the equivalent linearity. As the input ground motion intensity increases, the soft rock gradually enters a nonlinear state, and the ground acceleration amplification factor gradually decreases.

In this paper, the one-dimensional equivalent linear method and two-dimensional nonlinear method are adopted, and the seismic response characteristics of soft rock sites are preliminarily compared and analyzed. For further research, the three-dimensional model calculation and analysis can be considered, especially for the calculation and analysis of complex sites, which can further elucidate the dynamics of these sites.

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