Numerical analysis of dynamic responses of expanded piles subjected to earthquake loadings

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Abstract. Expanded piles, a novel type of pile system equipped with special mechanical structures, are found with significantly enhanced mechanical performances such as anti-pulling and anti-shearing capacities due to the deformable expanding disks in the middle part. As these structures are generally new, their dynamic responses subjected to earthquake are still unclear. Based on the finite element method, the expanded pile-platform structure is first modelled locally and globally in details. Then, by using the acceleration-time information, the dynamic responses of the expanded pile-platform structure are studied to obtain its deformation properties and envelop diagrams of internal forces, which are compared to the results of normal pile-platform system. The obtained results will assist the designers and engineers to better understand the dynamic responses of the expanded pile-platform structure, thus correspondingly optimizing the reinforcement design and enhancing the dynamic safety of the structures.

1. Introduction

Expanded piles can be adopted to fully utilize the bearing capacity of the soils around the piles due to the presence of branches and plates. Compared to normal grouting piles, expanded piles are characterized by greatly increased vertical bearing capacity, good anti-pulling, shock absorption and energy conservation performance, so they’re widely applied in the engineering projects [1].

Currently, domestic and international scholars have conducted studies on expanded piles. For example, Wang Anfu et al. [1] surveyed the research status of these piles, experimented their bearing mechanisms, and proposed a series of novel core technologies for future expanded piles; Wang Yili et al. [2] adopted the finite element software Abaqus to analyze the bearing capacity, settling capacity and other vertical bearing features of expanded piles, and also discussed the optimal spacing of bearing disks; Based on on-site static loading test, Wang Youkai et al. [3] measured the changes in axial forces of expanded piles, and investigated their vertical load displacement characteristics; In combination with numerical methods and field testing technologies, Yin et al. [4] explored the consolidation settlement features of expanded piles; By designing modelling experiments, Wei et al. [5] studied the bearing capacities and deformation features of expanded piles under combined loadings; Chen Fei et al. [6] conducted in-situ testing on expanded piles, and the testing results suggested that...
the side resistance and loading plate resistance showed obvious time order effect; Ju Yuwen et al. [7] revealed the failure mode of piles with branches and plates and improved the calculation theories of bearing capacity of these structures through loading test on their model specimens.

As a novel pile system, expanded piles mainly receive the load from upper structures and spread the load to the foundation, making it possible for the settlement and deformation of the buildings to fall within the limits. As a result, the existing studies mostly focus on theoretical analysis and calculation of vertical bearing capacity and deformation, the distributions of friction resistance at the pile side, the pile end and the branches and plates as well as their aging effects. The earth is geologically active, and earthquakes have frequently occurred in recent years. The foundation has a great impact on seismic performance of the buildings [8], so it establishes the need of exploring mechanical properties of expanded piles under the earthquake effect. Numerous scholars have studied the stress behaviors of pile structure subjected to earthquakes. For example, Zhao Liping et al. [9-12] employed finite element method to analyze the seismic performance of pile foundation. Nevertheless, expanded piles are rarely studied under earthquake effect.

To make up for the deficiency, the expanded pile-platform structure is modeled in details by using the finite element software Abaqus, and the mechanical responses of the structure subjected to earthquakes are explored. In this way, the deformation and internal force features of expanded piles are obtained, and some rules are summarized, thus facilitating the designers and engineers to optimize their designs.

2. Methodology

2.1. Overview of dynamic calculations based on finite element method

According to the finite element method, the physical model is geometrically discretized into many micro units, which form a complete structure through nodes. In Abaqus, displacement is calculated on nodes, while stress and strain are computed on stress points; the integral of the pile section is calculated for internal forces of the pile.

The inertia force is generally listed separately, thus obtaining the following dynamic balance equation:

\[ M\ddot{u} + I - P = 0 \]  

where M is the mass matrix, which is generally irrelevant with time; I and P are two vectors related to displacement and velocity, revealing the impacts of damping and energy consumption. I is defined as:

\[ I = Ku + C\dot{u} \]  

If stiffness matrix K and damping matrix C are constants, it becomes a linear system problem; otherwise, a nonlinear system problem shall be solved.

By substituting Eq. (2) into Eq. (1), we obtain:

\[ M\ddot{u} + Ku + C\dot{u} = P \]  

The above dynamic balance equation incorporates all possible nonlinear impacts, and can be adopted to describe any feature of mechanical system. Therefore, it is the most common dynamic expression. The above dynamic equation can be solved by calculating the time-domain integral. Based on the discretization of spatial finite elements, partial differential control equations over time and space are converted into a group of coupled nonlinear ordinary differential equations.

Unlike static analysis, structural responses in the structural dynamic analysis are also closely related with the loading and boundary conditions and the initial status of the structure. By utilizing finite element method, and numeral integral is then adopted to obtain stress-strain and displacement responses of each time-domain point over the space.

For the purpose of dynamic analysis, if a system is linear or if a system can be linearized through appropriate methods, modal analysis is prioritized due to two reasons: it is efficient in analyzing linear problem; it can be used to have a better understanding of dynamic features of the expanded pile in the temporal and spatial ranges.
2.2. Modal analysis
Modal analysis is one of the methods for structural dynamic features. By converting physical coordinates of vibration differential equations into modal coordinates, these equations are further decoupled into independent equations described by modal coordinates and modal parameters.

Vibration frequency $\omega_i$ and modality $\Phi_i$ under modal analysis can be solved through the following equations:

$$([K] - \omega_i^2[M])\{\Phi_i\} = 0 \quad (4)$$

Here, it is assumed that $[[K]]$ and $[M]$ are constants; that is, the material is linear elastic.

Transient analysis module in Abaqus is utilized for dynamic analysis of the expanded pile foundation, especially for time history analysis. The prominent damping effect exerted by the surrounding soil shall be taken into account for two reasons: firstly, the filtering and amplification effects of site soil on seismic waves lead to greater changes in the waves on expanded pile foundation than those in the waves on the bedrock; secondly, since expanded pile cannot deform freely, the surrounding soil will amplify the mass effect of the structure.

3. Project simulation

3.1. Project Overview
The experiment involves 4 55m-long concrete-based expanded piles with circular cross section and a diameter of 1.8m, which are covered by a platform of 8m×8m×2.8m. The relations between 4 piles and the platform are shown in Figure 1. The pile foundation is buried in a soil stratum of 30m×30m×75m; the upper surface of top plate is on the same level of the foundation surface; the soil depth under the pile is 17.2m (one third of the pile length). The foundation bottom is subjected to 10s of acceleration (an acceleration period lasts for 10s), and the dynamic responses of the piles under the earthquake loadings are explored.

3.2. Establishment of numerical model

3.2.1. Modelling. The three-dimensional model is established in Abaqus for two parts: pile foundation (material: C30 Concrete), foundation (material: silty clay, fine sand).

First of all, a three-dimensional foundation model is built. As shown in Table 1 and Figure 1, the rotation method is adopted to build 55m-long concrete-based expanded piles with circular cross section, which has an upper diameter of 1.8m, a variable section diameter of 1.4m and an expanded diameter of 2.5m, as well as 55m-long concrete-based normal piles with circular cross section that has an upper diameter of 1.8m and a variable section diameter of 1.4m; then, the tension method is utilized to shape an 8m×8m×2.8m concrete slab. The slab and the piles are assembled as indicated in Figure 2.
Table 1 Soil Distribution in the Foundation of the Proposed Model

| Pier number | Pile length (m) | Location | Elevation (m) | Soil layer | Reference drilling |
|-------------|----------------|----------|---------------|------------|-------------------|
| 37#         | 55             | Pile top | -0.503        | /          | XCDD-SQZK15       |
|             |                | Upper plate | -28          | Silty clay |                   |
|             |                | Six Star Branch | -33         | Silty clay |                   |
|             |                | Six Star Branch | -37         | Silty clay |                   |
|             |                | Middle plate 1  | -42          | Silty clay |                   |
|             |                | Middle plate 2  | -47          | Fine sand  |                   |
|             |                | Bottom plate    | -52          | Silty clay |                   |
|             |                | Pile bottom    | -55.503      | Silty clay |                   |

Secondly, a three-dimensional foundation model is established. A foundation (30 m×30 m×75 m) with 4 layers of soils is built, as shown in Figure 3. Then, the pile foundation is cut down at corresponding site of the model.

Figure 2 Schematic Diagrams of Expanded and Normal Piles

Figure 3 Schematic Diagram of Three-dimensional Foundation Model
3.2.2. Material parameters. The proposed model requires 3 kinds of materials: silty clay, fine sand and concrete. Based on existing references and geological survey reports, the dynamic characteristics of soil are considered, and the parameter values are given in Table 2.

Table 2  Material Parameters for the Proposed Model

| Category    | Density (kg/m³) | Dynamic Elastic Modulus (MPa) | Poisson’s Ratio | Cohesive Strength (Pa) | Internal Friction Angle (°) |
|-------------|-----------------|-----------------------------|-----------------|------------------------|-----------------------------|
| Silty Clay  | 1,900           | 200                         | 0.3             | 20,000                 | 20                          |
| Fine and Concrete | 1,950   | 720                         | 0.25            | 6,000                  | 34                          |
| Concrete    | 2,330           | 30,000                      | 0.2             | --                     | --                          |

3.2.3. Step Setup. Modal superposition method is adopted for analyzing dynamic responses of pile foundation subjected to earthquake. Firstly, the steps “Frequency” and “Modal Dynamics” are created; over the same period, the damping is taken into account (with a damping coefficient of 0.03), and the damping is set up as shown in Figure 4.

3.2.4. Step Setup. In the Fre Step, the model undersurface is fixed, namely, U1=U2=U3=0; Since the foundation bottom is subjected to horizontal acceleration, the model is set to displace along U2 and U3 directions. In the Dyna Step, according to the data provided, the earthquake acceleration curve is shown in Figure 5. The acceleration curve in Case 1 is defined in diagrams and exerted onto the bedrock. The boundary conditions of the acceleration are set in Figure 6.
4. Analyses and discussions of results

4.1. Type and frequency of vibration
With the help of Abaqus, the results of expanded and normal piles can be obtained as follows:

| Modality | 1     | 2     | 3     | 4     | 5     |
|----------|-------|-------|-------|-------|-------|
| Eigenvalue | 23.029 | 191.44 | 510.77 | 552.00 | 771.22 |
| Frequency  | 0.76377 | 2.2021 | 3.5969 | 3.7393 | 4.4199 |

| Modality | 1     | 2     | 3     | 4     | 5     |
|----------|-------|-------|-------|-------|-------|
| Eigenvalue | 22.969 | 191.18 | 510.63 | 550.73 | 769.84 |
| Frequency  | 0.76276 | 2.2021 | 3.5969 | 3.7393 | 4.4159 |

Figure 5 Earthquake Acceleration Curve

Figure 6 Setup of Boundary Conditions for Acceleration
4.2. Internal forces and moments
When horizontal acceleration is applied, the stress and deformation of pile foundation within 85s are dissected by utilizing modal superposition method. By obtaining the sections of pile foundation along the depth direction, its internal forces and moments under earthquake loading are obtained.

The analytical results show that expanded piles have excellent shearing force Fx along x direction and satisfactory moment My along y direction. By comparing the distributions of shearing force (Fx), axial force (Fz) and moment (My) over the 85s along the depth direction, the following envelop diagrams are obtained.

![Figure 7 Envelop Diagrams for Shearing Force](image-url)
According to the analytical results, axial and shearing forces at the variable section and foundation of expanded pile increase significantly, while the moment at the pile top and variable section expands obviously. Therefore, time history analysis is conducted on the axial force $F_z$, the shearing force $F_x$ and the moment $M_y$ for the top ($z=-0.503\text{m}$) and variable section ($z=-20.503\text{m}$) of expanded pile, as shown below:
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Based on the above analyses, it can be known that there is large stress at and between the expanded plates.

4.3. Discussions

Abaqus is utilized to analyze the dynamic responses of pile foundation. The following comparisons are conducted for expanded and normal piles subjected to periodic earthquake loadings under the same conditions:

(1) Shearing Force Distribution: It is found through the comparisons in Figure 10 that under the same earthquake loading over the same period, the largest shearing forces for both piles are concentrated in the lower part, and the shearing force suddenly increases at the variable section (namely, z=-20.503m). Yet, expanded pile experiences greater sudden increase in shearing force, especially at the variable section and the expanded plate. To be specific, expanded file is founded with the largest shearing force at the underplate (namely, z=-52m), which is about -7,300kN; in contrast,
the largest shearing force in normal pile goes downward at the pile bottom (namely, z=-55.5m), which is about -7,800kN. Overall, there is a small difference between the shearing forces for both piles.

(2) Axial Force Distribution: The comparisons in Figure 11 suggest that both piles have a huge difference in axial force under the same action time. In expanded piles, the axial forces at the variable section and the expanded plate suddenly change on a frequent basis; the maximum axial force occurs at Six-star Branch (z=-37m), which is about ±440kN. In normal piles, the maximum axial force occurs at the pile top, which is approximately ±500kN; the axial force suddenly changes at the variable sections (z=-20.503m, -42m, -47m and -49.5m), especially at z=-49.5m where the axial force reaches ±440kN. It is speculated that at z=-42m, -47m and 49.5m, the sudden changes in axial force are caused by soil dislocation at the division surfaces. Compared to normal piles, expanded piles have smaller maximum axial force from the global view, but greater axial force at specific sites.

(3) Moment Distribution: According to the comparisons in Figure 12, both piles basically experience the same changes in moments under the same action time, but expanded piles have larger maximum moment (about ±8,200kN·m) than normal piles (about 6,500kN·m). At the first point with sudden change in moment, the increased moment for expanded piles is about 2,500kN·m greater than that for normal piles (about 5,000 kN·m for normal piles and 7,500 kN·m for expanded piles), and the moment of normal pile does not suddenly change at the variable section (z=-20.503m), and the point with sudden change goes upward at z=-15m. Obviously, normal piles generally have smaller moment than expanded piles.

In general, the maximum moment occurs at the pile top, but in our case, larger moment is found not only at pile top but also within the intervals (-20m, -10m) and (-50m, -40m), such as variable sections and boundaries of soil layers.

5. Conclusion
In this paper, dynamic responses of expanded pile-platform structure are explored based on finite element method, and the internal forces and deformation features of the structure under dynamic loading are obtained. The results suggest that compared to normal piles, in addition to platform bottom, internal force may also suddenly change at the variable sections and boundaries of soil layers for expanded piles, so reinforcement and design at these sites shall be further optimized.

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