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Optimization Analysis on Seismic Mitigation of Building Foundation in Coastal Area

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Optimization Analysis on Seismic Mitigation of Building Foundation in Coastal Area

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Abstract. The stability of the buildings foundation in coastal areas caused by the submarine earthquake caused by the seabed plate movement has increasingly become the research focus of the engineering construction department. For the foundation under special geological conditions in coastal areas, the failure mechanism is complicated and the stress analysis is difficult. Based on the current situation of seismic design of building foundation in coastal areas, and aiming at the immature aspects of seismic treatment of foundation in coastal areas, this paper analyzes the optimization scheme of seismic design of foundation in such areas, which provides reference ideas for seismic design of building foundation in coastal seismic zones in China. In this paper, the research method is mainly through the comparative analysis of the relevant coastal engineering foundation treatment cases, the comparison of their treatment schemes and the combination of the existing foundation damping theory to summarize the suggestions on the foundation damping design under the special geological conditions in China's coastal areas. In this paper, it is suggested that two aspects should be considered in the design of foundation vibration reduction in coastal areas: the application of dampers to reduce the vibration of foundation structures and the reinforcement of rock and soil under the foundation to meet the requirements of vibration reduction.

Keywords: Submarine earthquake, Coastal areas, Buildings, Foundation seismic mitigation.

1. Introduction

In recent years, with the steady scale construction of a series of super-large marine facilities, such as coastal nuclear power plants, sea-crossing bridges, artificial islands, etc., China has shifted from developing the ocean to building a powerful ocean power. The impact of seabed plate movement on these coastal projects has increasingly become the research direction of relevant departments. As one of the most important forms of submarine plate movement, submarine earthquakes have the most obvious destructive power. At present, there have been cases of coastal or offshore engineering damage in earthquakes abroad [1-2]. As the foundation of a building, it will be damaged directly or indirectly by the earthquake in the first place. First of all, the change of mechanical properties of rock mass in the foundation area caused by earthquake cannot be ignored. Pan Bietong (1992) classifies fracture mechanics research and rock mass hydraulics research of rock mass fissures as rock mass mechanics problems of geological disaster events [3]. The distribution of rock and soil bodies in China's coastal areas mainly includes approximately 35% of granite which is not easy to be eroded by groundwater and generally has no active faults, and approximately 65% of stratiform metamorphic rocks, sedimentary rocks, medium-hard soil and medium-soft soil which are easy to be eroded by groundwater and have active faults [4]. It can be seen that the rock and soil bodies in the coastal seismically active zone are easily affected by both the rock fissures caused by the earthquake and the seepage of groundwater. At present, relevant researches show that the seepage action of fractured rock mass will affect the deformation and stability of foundation works, for example, through the tests on the seepage characteristics of fractured surfaces [5-6]. Secondly, the site condition around the foundation is an important index that affects its seismic performance. Chen Guoxing (2007) classified the failure of foundation as one of the engineering problems of damage due to seismic waves [7]. The cause of foundation failure is related to sand liquefaction and uneven deformation caused by vibration. Both of the above reasons can occur during an earthquake. Uneven soil quality within the influence range of the foundation will lead to uneven deformation of the foundation during the earthquake. Loose sediments formed in coastal river deltas and plain areas are the main sources of sand liquefaction during earthquakes [8-9]. Based on the characteristics of geotechnical structures and the causes of foundation failure in coastal areas different from those in inland areas, it is shown that the seismic design of building foundations in coastal areas should not only understand the main distribution zones of coastal earthquakes, but also fully consider the mechanical properties of foundations and the influence of geotechnical bodies around foundations on their seismic performance.

Compared with the seismic design and construction of the foundations of onshore buildings in China, the research on the seismic performance of the foundations of offshore buildings is not yet mature, and the seismic analysis is generally based on the onshore strong earthquake records [10]. At the same time, the relatively complex geological characteristics in the coastal areas make the seismic design of the foundation more difficult. For example, the widely distributed soft soil and weathered zone in the coastal areas will directly reduce the seismic performance of the foundation. At present, the research on the seismic design of foundation in coastal areas in our country started relatively late and relatively few, especially the seismic design of foundation under such special geological conditions in coastal areas. Therefore, this paper will study the aseismic design of building foundations in coastal areas under special geological conditions, compare and analyze some aseismic design cases of building foundations in coastal areas, and get the support of the aseismic design cases of foundations. Finally, this paper will put forward some suggestions on the seismic design of foundations in coastal projects, which will provide some reference for the seismic design of foundations in coastal areas of our country.

2. The influence of submarine earthquake on foundation

China's coastal area is located at the extrusion intersection of Eurasia plate and Pacific plate, and the frequency of submarine tectonic earthquakes is relatively high. Therefore, it is of great significance to study the causes of submarine earthquakes and the failure mechanism of the foundation stability of coastal buildings for seismic mitigation design of buildings in coastal areas.

2.1. Causes of submarine earthquakes

The types of submarine natural earthquakes mainly include tectonic earthquakes and volcanic earthquakes. Among them, tectonic earthquakes account for more than 90% of all natural earthquake events and are the most worthy of study. Seafloor tectonic earthquakes are related to plate compression and strata dislocation, mostly occurring near submarine volcanoes and mid-ocean ridges far away from the mainland. Tectonic earthquakes near submarine volcanoes are tectonic movements caused by magmatic eruptions with a small impact range, and the seismic sources generally do not exceed 10 km [11]; The mid-ocean ridge is an important area for plate expansion and the most important active tectonic zone [12], and the tectonic earthquakes caused by it have a huge impact range. China is divided into 23 seismic zones, with Xinjiang and Tibet in the west and Taiwan Province in the east being the most obvious ones. Although the background of seismicity in western China is rich, earthquakes have a greater impact on the seismic zones of densely populated and economically developed eastern coastal city, especially Fujian seismic zone, Guangdong seismic zone and Taiwan Province earthquake zone.

2.2. Failure mechanism of submarine earthquake to foundation stability in coastal areas

After the submarine earthquake, the seismic wave energy is transferred to the surrounding of the foundation through the soil layer. At this time, the seismic wave energy is converted into the stress of the foundation and additional stress is applied to the foundation. When the total stress reaches the limit value, the foundation will lose stability [13]. At the same time, the damage and fracture of rock mass around the foundation caused by seismic waves is also the main factor causing the instability of the foundation.

Dynamic analysis method is currently the most widely used method to analyze the vibration effect of seismic waves in China, because the foundation is also affected by the vibration period and vibration duration of seismic wave in the medium such as rock and soil when it is damaged by vibration. The two influencing factors are closely combined with the type and structural characteristics of rock and soil, and only the principle of dynamic analysis can take the above situation into account [13].

When the dynamic analysis method is applied, the seismic wave acting on the foundation is regarded as simple harmonic vibration, and at the same time, the structural characteristics of the rock-soil body lead to the existence of damping. At this time, the characteristic spectral lines of the maximum acceleration of the rock-soil single substance point and the natural frequency of the particle can be obtained under the condition of a certain damping ratio, and the stress state of the particle can be deduced through the spectral lines. However, according to the research, it is proved that the fracture of rock and soil mass is not only related to the particle stress but also the result of the coupling of the stress condition and the seepage action [14-16], that is, the change of the stress state of rock and soil mass and the seepage action of water lead to the damage and fracture of rock and soil mass.

For seepage, the vibration effect caused by the earthquake causes the soil particles to be in suspension while the seepage force of water takes away the local particles, which eventually causes the deformation of the local rock and soil, thus causing the instability of the foundation.

The following is a simple combination of the coupling effects under the two conditions.

Based on the dynamic stress, the stress of seismic wave on rock mass particles can be simply divided into the longitudinal stress δ_d caused by P wave and the shear stress τ_s caused by S wave, and their expressions are as follows:

$$\delta_d = \frac{a_p E}{2\pi f_p v_p} \quad (1)$$

$$\tau_s = \frac{a_s G}{2\pi f_s v_s} \quad (2)$$

a_p represents the particle acceleration of the P wave medium, f_p represents the P wave frequency, and v_p represents the propagation speed of P wave.a_s represents the particle acceleration of the S wave medium, f_s represents the S wave frequency, and v_s represents the S wave propagation speed.

Based on the characteristic spectral lines, the damping ratio can be obtained by empirical formula. The damping ratio λ in this section is obtained by the λ — curve relationship made by Chen Guoxing and others [17-19]. The natural vibration period of the structure is related to the mass and stiffness of the structure itself and therefore is not considered as the main variable.

Based on the seepage action, the anti-seepage strength of rock and soil is an important index to judge the permeability of soil. The anti-seepage strength is closely related to the particle diameter, coarse and fine soil content, soil gradation and particle shape of soil. Because of its complexity, it is difficult to obtain it directly by formula. In engineering, it is generally obtained by chart method and on-site direct test.

Taking the soft soil layer in the coastal area as an example, when the local seismic wave propagates to the shallow layer of the foundation, the soil around the foundation has smaller particle diameter, higher content of fine-grained soil and higher water content and porosity. When the gradation and particle shape are fixed, the particles in the soil are more likely to be carried away by water, and the compactness of the soil is reduced. Furthermore, the damping ratio of the soil is small, and the maximum acceleration (or maximum displacement and maximum speed) of particles in the soil is higher. According to the formula (1)(2), it can be known that the longitudinal stress and shear stress to which the foundation rock mass is subjected are greater, and when or, the foundation rock mass will break longitudinally or tangentially, the energy of the seismic wave will be converted into the strain energy of the rock mass, thus damaging the stability of the foundation.

2.3. Traditional seismic mitigation methods for foundation in coastal areas

The special geological conditions in coastal areas have put forward higher requirements for seismic mitigation. At present, the most widely used foundation damping method is to consume a part of energy in the foundation soil layer through an energy dissipation device in the process of the seismic wave propagating to the building body above the foundation, so as to reduce the energy transmitted to the upper building structure, simultaneously reduce the dynamic stress response caused by the seismic wave and reduce the interlayer shear stress in the X and Y directions of the foundation. At present, there are three kinds of energy dissipation and seismic mitigation methods commonly used in engineering: damper method, seismic mitigation trough method and soil improvement material [20].

2.3.1. Traditional energy dissipation and seismic mitigation method. Setting damper: The principle is that the damper can consume part of the energy of seismic wave propagation, and the purpose is to set the damper in the foundation and superstructure to change the vibration characteristics of the structure: increase its vibration damping and prolong the natural vibration period of the structure. At present, the dampers are mainly classified into friction dampers, metal dampers, lead dampers, viscoelastic dampers and velocity dampers [21]. However, it has the disadvantage that different dampers can only be used in a suitable range, and the structural characteristics and damping purpose should also be considered when selecting. For example, viscoelastic damping can greatly improve the seismic performance of some steel structures under the action of long-period seismic waves [22-23]; Another example is to set velocity-dependent and displacement-dependent dampers in the foundation where the relative displacement between layers is easy to occur.

Positioning the damping groove: The main idea is to arrange a rectangular groove at a certain distance from the seismic source. The larger the depth of the trough is, the closer it is to the source, the stronger the seismic mitigation effect is. It has been pointed out that when the depth of the trough is 30m, the seismic mitigation in the near region can reach more than 90% [24]. However, it is necessary to ensure a reasonable size and placement position during installation to achieve an effective seismic mitigation effect.

Improving of soil layer materials: The function of such materials is to absorb the energy transmitted by seismic waves in the soil and transform it into its own elastic-plastic deformation, which is often placed in the shallow layer of the foundation as a shock-isolating and seismic mitigation layer during construction. At present, the materials that can be used to improve the soil layer include sand cushion, sand bag cushion, gravel cushion, modified asphalt shock-isolation cushion, reinforced asphalt composite shock-isolation layer, rubber particle sand mixture, soil bag pile [25], etc.

2.3.2. Case selection. In this paper, two engineering examples using the above-mentioned damping method are selected.

Case 1: Terminal 3 of Shenzhen Bao'an International Airport [26]

Shenzhen Bao'an International Site is located at the estuary of the Pearl River Delta, with marine and continental sedimentary strata. The soil in this area is classified as muddy soft soil in engineering geological exploration, with poor engineering properties and site type II site soil. The historical earthquake data show that shallow earthquakes are the main place here, with seismic fortification category B and fortification intensity of 7 degrees. Based on the fact that the foundation of the airport is greatly affected by the soft soil, the velocity type viscous damper is adopted as the structural damping design in the project. Due to the effect of the damper, the maximum relative displacement of the structure is reduced from 190mm to 61mm, which is about 67.9% lower.

Case 2: Qingdao Jiaodong International Airport Terminal [27]

The terminal building is located near the boundary line between Subei-Jiaonan fault block and Jiaoliao fault block. It may be mainly affected by the earthquake in the Yellow Sea seismic belt. The site type is Class II site soil, and the basement is located above the fully weathered zone and the strongly weathered zone of argillaceous siltstone, with poor engineering geological conditions. At the same time, as it is located in multiple fault zones and seismic zones, the project is mainly fortified according to the seismic fortification category of the Code for Seismic Design of Buildings, with a fortification intensity of 7 degrees. A relatively safe velocity-dependent viscous damper is adopted, which can keep the foundation and above structures in an elastic state when an earthquake occurs. With 7 groups of seismic waves, the mean value of the maximum shear stress of the foundation with and without dampers is reduced by about 29% and the maximum interlayer displacement angle is reduced by about 42% after the test. With the addition of appropriate dampers, the energy consumption of seismic waves on the foundation is significantly increased. The literature indicates that approximately 30% of the total input energy of seismic waves is converted into other forms of energy such as thermal energy by the dampers.

3. Optimization of traditional seismic mitigation methods

Suggestions on seismic design of building foundation in coaBased on the particularity of engineering geological conditions in coastal areas, the above-mentioned damping method has certain limitations in practical application in coastal projects. Especially, when the foundation of coastal projects is located on soft soil and strongly weathered rock, the seismic performance of the foundation is different, and the methods such as dampers can no longer provide the optimal damping effect alone. At this time, the reinforcement and damping measures for the rock and soil around the foundation need to be considered.

3.1. Comprehensive analysis of the above cases

Shenzhen Bao'an International Airport is located in the estuary area where marine sediments are deposited. The soft soil layer is thick. In the later stage of the airport expansion, the method of inserting plates and preloading is applied to reinforce the foundation. In addition, further reinforcement and anti-seepage treatment may be considered for the rock and soil within the influence scope of the foundation under the terminal building. Based on the characteristics of high water content and large void ratio of silt soft soil, the vacuum combined water-coating preloading method can be considered for reinforcement, which is characterized by combining the respective advantages of the vacuum preloading method and the surcharge preloading method, and achieving remarkable effects in the aspects of reinforcement depth, settlement control and the like. At the same time, the grouting method is adopted to reduce the formation permeability below the foundation, so as to avoid the possible influence of shallow earthquakes nearby on the formation permeability below the airport.

Qingdao Jiaodong International Airport is located in several fault zones and seismic zones. At the same time, its foundation is located in the weathered zone of argillaceous siltstone, which is easy to break. When vibration breaks, it may form a concentrated seepage path to aggravate the damage to the foundation. Considering this, the project located on the similar soil layer can pour filling material into the broken voids in the weathered zone below the foundation to improve the seismic strength of the rock and soil mass. At the same time, according to the particle size of the argillaceous siltstone, an appropriate filter screen for the well point pipe filter section of the dewatering well is selected to prevent the smaller particle size from being carried away after the seepage path is formed.

3.2. Applicability of optimization scheme

The foundation of Haikou Meilan International Airport T2 Terminal is located on the shell clastic rock stratum [28], with obvious holes and serious water leakage during drilling. The designers adopted the post-grouting technology at the pile tip to increase the grouting amount for the shell clastic rock stratum. The total settlement of the foundation under the ultimate load recorded by the engineering inspection is 19.95～21.61mm in some areas of the site which meets the specification requirements.

At present, the vacuum combined water-coating preloading method has been applied in large-scale projects, and is mainly used for reinforcing large-area soft soil foundations. The water content and void ratio of the soil after the National Food Safety (HengQin) Innovation Center [29] uses the water-coating vacuum preloading method to treat the silt soft soil foundations are reduced by 15.1% and 14.6%, respectively. The average settlement rate measured at the end of the field test is 0.1cm/d, which meets the acceptance criteria.

4. Suggestions on seismic design of building foundation in coastal areas

Based on the failure mechanism of foundation stability, the seismic design of building foundation in coastal areas can be carried out from the following two aspects:

For the seismic mitigation of foundation structures, designers should adopt appropriate dampers to dissipate the seismic waves, prolong the natural vibration period of the structures and reduce the dynamic stress response of the structures, so as to reduce the shear force between the foundation layers and avoid the shear failure of the foundation during earthquakes.

For the seismic mitigation of rock and soil under the foundation, drainage consolidation should be carried out on the coastal soft soil layer to reduce its water content and porosity ratio and improve its compactness. The rock mass in the weathered zone is grouted and reinforced to reduce the void volume ratio contained in the fractured zone, so as to avoid uneven settlement and deformation of the foundation caused by soil collapse caused by the formation of concentrated seepage path due to void expansion.

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