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The influence of earthquakes on Zhubi Reef in the Nansha Islands of the South China Sea

GUO Lei[1, 2], ZHAN Wenhuan[1*], ZHANG Fan[1], ZHANG Jinchang[1], YAO Yantao[1], LI Jian[1, 2], FENG Yingci[1, 2], CHEN Mei[1, 2], CHENG Gong[3]

[1] Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] Sinopec Geophysical Corporation Shengli Branch, Sinopec Oilfield Service Corporation, Dongying 257100, China

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Abstract

It is exceedingly important to estimate the stability of coral reefs. In recent years, growing construction projects have been carried out on the reef flat in the South China Sea. As a special marine geotechnical medium, it is made of the reef debris underwent overwhelmingly long geological age. Reefs grow thickly on the carbonate platform after the Late Oligocene and have five to six main sedimentary facies. It can be used as a recorder to measure the occurrence time of recent earthquake. A model of reef body is presented to study the influence of earthquakes according to the geological structure characteristic of reefs in the Nansha Islands. Furthermore, GeoStudio is used to simulate stress and deformation situations within it under various earthquake intensities. A safety factor is calculated by the limit equilibrium method, and the possible scenarios of earthquake-induced landslides and sliding scale are defined with a Newmark sliding block method, as well as stress distribution and deformation behaviors. Therefore, the numerical results suggest that the connections between the coral reef and the earthquake are as follows: (1) the reef body has a good stability under self-gravity state; (2) after the earthquake, it may cause slope's instability and bring out slumping when the safety factor is smaller than 1 (F_S<1); (3) the safety factor decreases with the increasing earthquake intensity, and fluctuates around a particular value after a while; and (4) as a new developed part of the reef, the smaller shallow landslide will be easily subject to collapse caused by the earthquake. It is concluded that it is feasible to provide a reference for evaluating the stability of coral reef using a geotechnical engineering simulation method. This can help the engineering constructions in the South China Sea.

Key words: Zhubi Reef, earthquake, limit equilibrium method, safety factor, Nansha Islands, South China Sea

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1 Introduction

Coral reef is a special kind of geological body that constructed by comprehensive biological processes (Zhu et al., 2014), and the appearance is attached by living corals. The development of reef landform is closely related to a climate, a sea-level change, and its adjacent water dynamic conditions, as well as a tectonic subsidence and seismic activities (Zhan et al., 2002). The Nansha Islands are located in the southern South China Sea (SCS). This area is limited explored despite numerous oil and gas discoveries in the shallow water areas around the basin. In this area, the quantities of coral reefs are developed, such as atoll, table reef, and nab, etc., among which the distinct atoll is the predominant type. Moreover, with more than 60 atolls in the Nansha Islands, it is an ideal platform for a hydrocarbon resource's exploration (MOETASNI, 1996). Increasing constructions, including ocean weather stations and airports, have been built on reef platforms, which are composed of coral debris, reef debris, and calcareous sand, etc. (Yu et al., 2012). Unfortunately, poor understanding and improper selection of designing methodology have led to many construction failures in many years (Wang et al., 2011a). Therefore, it is extremely important to estimate the stability of coral reefs and investigate the engineering geological characteristics of reef in the Nansha Islands.

It is feasible to study the reef and earthquake interactions. Previous studies of reefs have emphasized a potential recorder to neotectonic movements. Coral reefs have been widely used to reveal longer-term environmental variations, including Holocene high-resolution sea surface temperature and abrupt climate events, millennial- and centennial-scale sea level oscillations, etc. The early work of Taylor et al. (1987) has shown that the coral reef can be used to study the earthquake. A quintessential example should be cited that it could be used to measure the occurrence time of recent earthquake by the thorium-230 ages of corals, which has been turned out to be accurate in the Vanuatu Is-

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*Corresponding author, E-mail: whzhan@scsio.ac.cn

lands (Edwards et al., 1988). Zhan et al. (2006) have discussed the evolvement process of coral reef in the SCS, which indicated that modern earthquake could be recorded in reefs. Nevertheless, there are few studies about the influence of earthquake on a reef. Qualitative and quantitative analyses for earthquake's influence on the reef body are nearly unknown in this area.

In order to prevent the potential seismic subsidence hazard, it is indispensable to make a risk prediction for earthquakes in this area. We study the stability of reefs under earthquakes using the GeoStudio. It is a set of professional simulation software in geotechnical engineering. It also has been successfully used to analyze the stability of rock mass slope, to calculate the stress field of a dam, to do dynamic security check of structure, as well as to measure dynamic response of structure under seismic action (Xie, 2013; Wang et al., 2013a; Meng and Su, 2010), which allowing us to establish a geological model for further study. In addition, core drillings on the reefs have provided the most intuitive base data for studying the geological structure of coral atolls. In order to supplement the research data of coral reef and provide a foundation for future construction in the Nansha Islands, the influence of earthquake on reef is quantitatively investigated in this study. The results are also potential reference data for the engineering projects in the Nansha Islands of the SCS.

2 Geological setting and earthquakes

2.1 *The geology of carbonate reefs in the Nansha Islands*

The coral reef usually live within the sea area that the surface temperature reaches 20°C. Most of them live in the depth of 25 m or below 25 m deep water. They grow intensely rapidly in the truly rough sea area (Liu and Wang, 1997). The geological structure is extremely complex (Liu et al., 2009). Moreover, in the numerous SCS reefs, there is a big variation in areas ranging from less than 1 km^2 to more than 100 km^2, and the diameters varies from 1–2 km to 50–60 km (Wang, 2008). In addition, the Nansha Islands is located at the junction of the modern Eurasian plate, the Pacific plate, and the Indo-Australia plate. Most of the islands are atolls in this area, only a few of them are platform reef. From the point of regional view, the Cenozoic structural evolution of the area is closely related to both the proto-South China Sea and the South China Sea. From the point of global view, the Cenozoic structural evolution of the Nansha Islands is closely related to both the Tethys tectonic domain and the west Pacific tectonic domain. Furthermore, Nansha block is surrounded by a lithospheric fault, where the north margin is the junction of an oceanic crust and a continental crust. It is also contact with the central basin of the SCS (Zhou et al., 2005; Lü, 2012).

The study area is located at the southern margin of the SCS oceanic basin, which was deformed by strong Cenozoic extensional tectonics and reflected a magma-poor rift system at the initial stage of mantle unroofing. Carbonates were initiated in the Late Oligocene. There was a widespread carbonate platform developed across the Nansha Islands, concurrent with the period of sea floor spreading in the southwest sub-basin of the South China Sea between the Late Oligocene and the Early Miocene. Carbonates have occupied the area of the continental slope, the crust of which has been rifting to form cuestas. After the Early Miocene, the carbonate platform died due to the continued rising sea level and a quick subsidence. Some reefs continued their lives upon some structural highs, even to recent decades (Chang et al., 2015; Ding et al., 2013, 2015; Steuer et al., 2013). Consequently, the indications for shallow-water carbonate reefs can be interpreted to represent the platform carbonates.

2.2 *Earthquakes*

There are few earthquakes in the interior of the South China Sea Basin. Most of the earthquakes in the SCS occur in a subduction zone or along the Asian continental shelf. Earthquakes in the interior of marginal basins are extremely rare (Wang et al., 1979). According to the latest data of the United States Geological Survey (USGS)(http://earthquake.usgs.gov/), the greatest earthquake of modern times in the study area occurred in 1965 (epicenter: 12.347°N, 114.485°E) with magnitude of 5.9 and depth of 20 km. It is considered that the 1965's earthquake is the greatest one in the interior of the marginal sea (Wang et al., 1979). The focal mechanism demonstrated an almost pure thrust fault, which may indicate a horizontal compression within or across the plate. However, the greatest 1965's earthquake belongs to an intraplate one (Wang et al., 1979). Most regions in the Nansha Islands are steady or relatively steady, thus it is suitable for all types of engineering construction (MOETASNI, 1997a).

Zhubi Reef is a typical closed atoll in the northern part of the Nansha Islands. And it is also near the epicenter of the 1965's earthquake, about 100 km to the south (Fig. 1). In addition, there are many engineering constructions in the Zhubi Reef. Therefore, we select the Zhubi Reef as a main object to study the influence of earthquake on reefs. It is located in the northern margin fault zone of the Nansha Islands, which have moderate-intensity active faults (MOETASNI, 1997a). The Zhubi Reef is a Holocene active reef with length of 5.75 km, width of 3.25 km, and area of 16 km^2. Furthermore, the study area is on the south side of the seamount chain (Fig. 1), which used to be the location of the spreading ridge. Thus, the earthquakes are probably triggered by tectonic faulting. It is meaningful to make the research in this area.

3 Methods

We use GeoStudio software to calculate the stress field and the critical slip direction on the slope. Two methods are included in GeoStudio: limit equilibrium slice method and Newmark analysis method. In the first place, the limit equilibrium slice method has been widely used to research the stability of slope under earthquake load (Li et al., 2007). In this method, the positions of potential slip surfaces and the safety factor are determined. In the second place, the Newmark analysis method is often used in slope stability analyses in conjunction with seismic activity (Wang et al., 2011b). The Newmark displacement of the reef body is conveniently calculated under different earthquake intensities. It is a rapid assessment method for regional seismic landslide susceptibility and hazards. In this study, we calculate the accumulated permanent displacement over the whole shaking process, which is helpful to analyze the slope stability. Consequently, the high-scale earthquake landslide-prone and high-risk areas are quickly locked, which provides evidence in time for the earthquake emergency response.

In addition, some basic assumptions must be adapted to these methods: (1) The geometric shape and the nature of loading on the slope should satisfy the conditions of the plane strain, thus the model can be simplified as a plane strain problem; and (2) Coulomb's strength principle is appropriate for the slop material (Xiao et al., 2011).

3.1 *Safety factor*

According to the shear strength criterion described in the Rock and Soil Mechanics, instability occurrence depends upon the shear stress and the shear strength on the slope (Xiao et al., 2011). The safety factor ($F_{S,\,i}$) is selected to be the standard, which

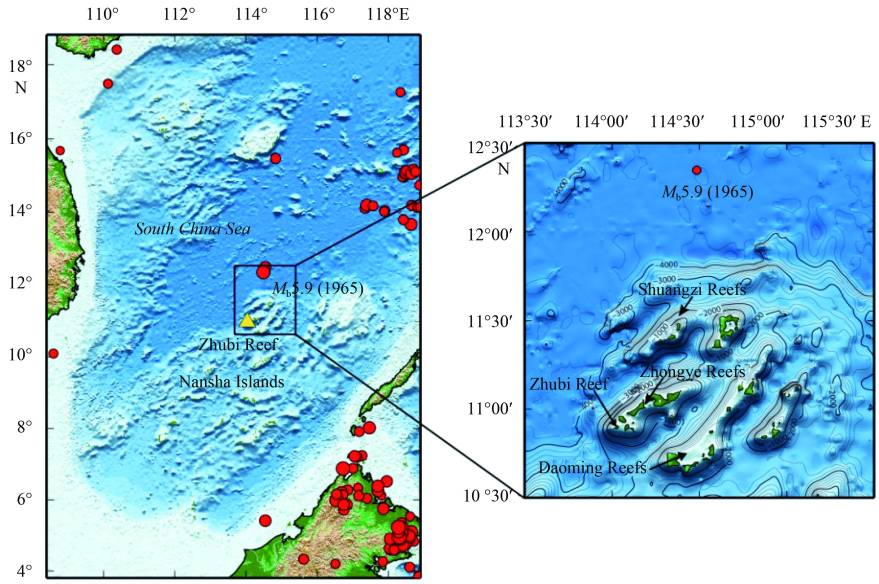

Fig. 1. Distribution of the earthquakes in the Nansha Islands. Red dots are the earthquake locations (M>4, 120 earthquakes in the map area). Yellow triangles mark the location of Zhubi Reef.

is defined as the ratio among the shear strength (S_i) and the shear stress (τ_i):

$$F_{S,i} = \frac{S_i}{\tau_i}. \tag{1}$$

For any point on the slope, if the safety factor is greater than 1, the point is stable; if the safety factor equals 1, the point is in the critical state of instability; or else if the safety factor is smaller than 1, the point is instable.

3.2 *Limit equilibrium slice method*

The limit equilibrium slice method is a predominant approach in analyzing the stability of slope, which is generally employed to evaluate the stability of the dam abutments in construction (Bao et al., 2011). According to the Mohr-Coulomb yield criterion, the shear strength of each section in each element should be limited within a certain critical value, which can be defined as (Wu, 2011)

$$S_i = c_i + \sigma_i \tan\varphi_i, \tag{2}$$

where c_i is the cohesion strength of each material, σ_i is the normal forces which are perpendicular to the slip faces, and φ_i is the internal friction angle of each material. Substituting Eq. (1) into Eq. (2), we obtained

$$\tau_i = \frac{c_i + \sigma_i \tan\varphi_i}{F_{S,i}} = \frac{c_i}{F_{S,i}} + \frac{\sigma_i \tan\varphi_i}{F_{S,i}}. \tag{3}$$

From the calculations, it can be concluded that when shear strength parameters (c_i, $\tan\varphi_i$) of materials are divided by the safety factor, the slope would meet the limit equilibrium conditions, where $F_{S,i}$ is the stability safety factor of slope.

3.3 *Newmark analysis method*

The Newmark analysis method has been widely used in the landslide risk assessment under seismic actions (Wang et al., 2013b). With this method, the accumulated permanent displacement is calculated over the whole shaking process, and the results are used to analyze the slope stability and the reef stability. The theoretical basis of this method is a limit equilibrium theory. It suggests that the permanent displacement is caused by accumulating displacements of the slide block along the most dangerous slip surface under an earthquake. As an example, the critical ground acceleration will have to overcome the block sliding resistance when the ground acceleration exceeds the slope's critical/yield acceleration (a_c). Then the down-slope movements will be initiated, and the stable movements of the block will begin to accumulate. If the critical acceleration of the slope (a_c) is known, the displacement can be calculated by double integrating all those values exceeding the slope's critical acceleration. The calculation process can be expressed as

$$D_N = \iint [a(t) - a_c]\,\mathrm{d}t\mathrm{d}t, \tag{4}$$

where D_N is the Newmark displacement, and $a(t)$ is the ground acceleration time history. The slope's critical acceleration can be calculated by

$$a_c = (F_{S,i} - 1) g \sin\alpha, \tag{5}$$

where g is the acceleration of gravity, and α is the slope angle.

4 Modeling and parameters

In order to verify the feasibility of the proposed method, a simple engineering geological model of the atoll (Fig. 2) is established to do the further researches according to the engineering geology zonation, lithological properties and rock mass structure characteristic of coral reefs in the Nansha Islands (Wang, 2008; MOETASNI, 1997b). The existing borehole data, seismic profiles, and other data are also taken into account into the modeling. It is an ideal model of Zhubi Reef. In this work, a self-gravity state and six kinds of earthquake intensity states (0.05, 0.10, 0.15, 0.20, 0.30, and 0.40 g, respectively), were discussed on the stress field and the reef stability by GeoStudio. Also, the limit equilibrium slice method and Newmark analysis method are applied as numerical calculation methods.

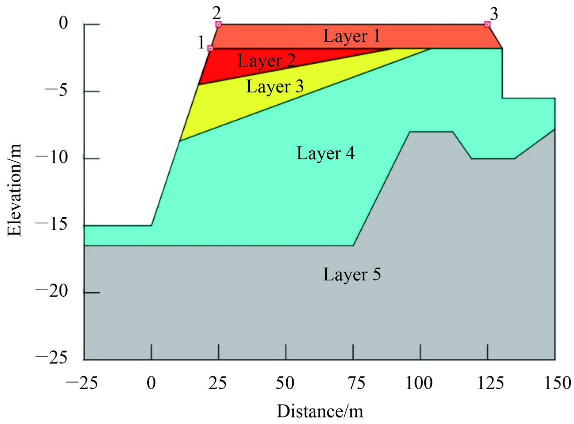

Fig. 2. A simple shallow engineering geological model of an atoll (Zhubi Reef).

4.1 *Modeling*

The modeling is based primarily on the seismic and drilling data. Detailed seismic interpretation and well data have proven that most carbonates started their growth since the Late Oligocene, and five tectono-stratigraphic units have been recognized in the Nansha Islands of the SCS (Ding et al., 2013, 2015). However, previous studies of these data are extremely limited in Zhubi Reef. We present to use the data of neighboring Reed Bank and Yongshu Reef, which are all in the north of the Nansha Islands, as reference. Newest reflection seismic data of this area are acquired in 2014. Combination results of the exploration well Sampaguita-1 (Taylor and Hayes, 1980) and drilling Nanyong-1, Nanyong-2 (Sun et al., 2003) indicated that the acoustic basements underlying the Daoming, Zhongye, Shuangzi Reefs, and Zhubi Reef were united before the rifting and opening of the South China Sea Basin (Chang et al., 2015). The differential subsidence between the bank and the trough occurred when the normal faults were activated. It became dominated by gravity-driven sedimentation after the cessation of the fault activities. Additionally, the giant reefs and upper part of the independent atoll of the Nansha Islands and reef knolls lying on the continental shelf were of the Quaternary period. Therefore, we propose that the deep structure is relatively stable in Zhubi Reef.

This study aims at presenting an overview of the relationship between earthquake and reef stability, and providing evidence for engineering stability evaluation and construction. In this study, we suggest to establish an ideal shallow engineering geological model of Zhubi Reef to analyze the stability under an earthquake. First and foremost is to determine the shape of Zhubi Reef. On the basis of the bathymetric and side-scan data, the shallow underwater topographic profiles are revealed including the lagoon, platform, seaward slope, and lagoon slope (Chen et al., 1994; Zhong et al., 1994). The center of the reef is a lagoon with a depth of 20–22 m. According to the topographic profiles of east reef flat and front, there are two obvious slope breaks at 8 m and 16 m depth, respectively, indicating a secondary underwater terrace. Therefore, combining the survey data with the sedimentary facies zones of the atoll (Zhu et al., 2014), we simplified the reef body and chose the part of the atoll to study the engineering problems. In the simple ideal model (Fig. 2), it shows that the reef platform is 100 m, the left slope is the lagoon slope with small gradient (30°–59°), and the right one is reef front with heavy gradient (5.7°–14°). The designed water depth of the lagoon is about 15 m. In addition, to meet the real reef, two secondary underwater terraces are designed at 8 m and 15 m, respectively. Second, it is indispensable to determine the strata and the lithology.

4.2 *Parameters*

To determine the strata and the lithology, some assumptions are made in this model. Previous seismic and drilling data mainly focused on reflecting the major characteristics of the deep structure on a carbonate platform in the Nansha Islands rather than the shallow structure in this area. In lacking of seismic data and drilling data in Zhubi Reef, we propose to use the data of Reed Bank and Yongshu Reef as reference for modeling and parameter selecting, which are also typical closed atolls in this area. The seismic profiles and drilling data of the adjacent Reed Bank manifested that there have been dominant topographies of carbonate reefs (Ding et al., 2015). The shallow part of Yongshu Reef is described as a huge rocky basin structure. The bottom of the rocky basin is formed by thick reef limestone (Meng et al., 2014). Smpagita-1 well has the greatest drilling depth (4 125 m) and provides the most complete stratigraphic sequence for this area (Taylor and Hayes, 1980). Moreover, four core drillings (Nanyong-1, Nanyong-2, Nanyong-3, and Nanyong-4) on Yongshu Reef (Zhao et al., 1992; Zhu et al., 1997; Yu et al., 2006; Meng et al., 2009), IODP site 1143 drilling data (Wan et al., 2006), and the reflection seismic profiles in Zhenghe-Daoming Trough (Chang et al., 2015) provide the most intuitive base data for studying the inner lithological characteristics in the atoll body.

Three main parts of rocky basin structure of the coral reef atolls are presented in the South China Sea: coral or gravel block, loose sand debris, and cemented reef limestone (Yu et al., 2014). The drilling data show that: 0–17.3 m hole depth sediments are Holocene ones, which consist of biological sand chips and medium sand containing gravel; 17.3–89.8 m hole depth sediments are composed of biological sand, gravel limestone, and coralline limestone (MOETASNI, 1997a; Zhu et al., 2014). In the model, the second part is further broken into three small layers that five layers in total. The primary parameters of each layer in the model are shown in Table 1.

The geotechnical characteristics are as follows:

(1) Layer 1. According to rock types of Nanyong-1 (MOETASNI, 1997a), the first layer is the gravel block layer, which mainly consists of biological gravel sand layer without cementation, mostly constitutes by coral gravel and coral block. The thickness of individual layer is 0–4.5 m. Common gravel diameter is 2.80 mm. According to the statistical data of physical-mechanical indexes of soils in the Nansha Islands, the saturated unit weight of coral block is 17–27 kN/m^3 (Sun et al., 2003; Wang, 2008), the cohesion is 2.1–27 kPa (Zheng et al., 2004; Liu et al., 2009). Additionally, the main recommended value of angle of the internal friction is 28°–32° (Cui, 2014). Poisson's ratio of sandy soil to calcareous sand is 0.20–0.25 and 0.25, respectively (Wang, 2008). In this model, we give a hypothesis that the thickness of Layer 1 is 2 m, the unit weight is 20.8 kN/m^3, cohesion is 28 kPa, the angle of the internal friction is 28°, and the Poisson's ratio is 0.25.

(2) Layer 2. The thickness of Holocene loosed coral debris ranges from 0 to 20 m. It deposits on the bottom of reef rocky basin. Layer 2 is gravel medium sand layer, which consists of loose bioclastic sediments, less gravel and more sand, coarse sand and many coral remain. The mean diameter of gravel is 0.46–0.90 mm. It is designed as a thin layer of 3 m thick and has sandstone up pinchout structure in it. With more sand and less gravel, we suppose that the unit weight is 22 kN/m^3, the cohesion is 20 kPa, the angle of the internal friction is 30°, and the

Table 1. Primary parameters of the model (Meng et al., 2014; Yu et al., 2014; Zhu et al., 2014; Cui, 2014; Wang et al., 2008)

Stratum	Lithology	Unit weight/kN·m^{-3}	Cohesion/kPa	Angle of internal friction/(°)	Poisson's ratio
Layer 1	biological gravel sand layer without cementation, mostly constitutes by coral gravel and coral block	20.8	28	28	0.25
Layer 2	gravel medium sand layer, which consists of loose bioclastic sediments, less gravel and more sand, coarse sand, and many coral remains	22.0	20	30	0.20
Layer 3	fine silt sand layer with gravel, which is similar to Layer 2 but has more sand, fine sand, and a few muddy	22.0	20	30	0.17
Layer 4	sand layer with coral branches, where the debris is basically the slightly abrasive and handled Acropora fragments	23.0	29	30	0.25
Layer 5	reef limestone with bioclastics, which is composed of weak cemented reef limestone with white or gray color, pores and loose debris	25.0	1 870	35	0.26

Poisson's ratio is 0.20.

(3) Layer 3. It is a fine silty sand layer with gravel, which is parallel and similar to Layer 2 but has more sand, fine sand and a few muddy. They all belong to Holocene loose coral debris. Its geotechnical parameters are same as Layer 2, where the unit weight is 22 kN/m^3, the cohesion is 20 kPa, the angle of the internal friction is 30°, and the Poisson's ratio is 0.17. The common diameter is 0.08–0.11 mm, which is smaller than Layer 2.

(4) Layer 4. From Layers 2–4, it can be considered as the lagoon slope sediments. And there is a flat in Layer 4 of 15 m in depth, which can be the bottom of the lagoon basin. It mainly consists of sand with coral branches, where the debris is basically the slightly abrasive and handled Acropora fragments. A particle size is 0.08–0.11 mm in diameter. With finer sand, we suppose that the unit weight is 23 kN/m^3, the cohesion is 29 kPa, the angle of the internal friction is 30°, and the Poisson's ratio is 0.25.

(5) Layer 5. It is reef limestone with bioclastics, which is composed of weak cemented reef limestone with white or gray color, pores and loose debris, reflecting a relatively strong stability characteristic. This layer is Middle–Late Pleistocene deposits and has an inner flat structure, indicating the influences of tectonic subsidence, sea level changes, and environmental factors. For Layer 5, we designed that the unit weight is 25 kN/m^3, the cohesion is 1.87 MPa, the angle of the internal friction is 35° (Wang et al., 2008), and the Poisson's ratio is 0.26.

5 Results and discussion

5.1 *Self-gravity state*

Figure 3 shows the effective stress distribution within the reef in the *X*-and *Y*-directions under a self-gravity state. Numbers on the contour lines are the stress values. It shows that the stress distributions within the reef body of two directions are both comparatively homogeneous, indicating that the reef body has a good stability under the self-gravity state.

It is crucial to do the risk prediction of reef edge slopes, which are an essential part of the atoll. Using the limit equilibrium method, the safety factorof the two slopes is calculated to be 1.977 and 2.072, respectively, under the self-gravity state (Fig. 4). The results demonstrate that the safety factor on both sides is high and much larger than the critical value of instability, thus the reef is relatively stable in this situation.

5.2 *Influence of earthquakes*

In this study, we simulated several kinds of seismic intensities using a simple ideal seismic wave record with 10 s length and analyzed their influence on the reef body, including the stress field, the deformed shape, stress, and acceleration change of single points within the reef body. According to the national standard (GB18306-2001) and the map of seismic intensity zoning worked by China Seismic Bureau, there are mainly six kinds of earthquakes intensities (Table 2). In addition, it should be noted that this study is only doing an idealized simulation, and it needs to be further amended for the real engineering problems.

5.2.1 *Analysis of stress field*

The impact of earthquake is reflected in the effective stress field inside the reef body. Figure 5 shows the stress field inside it under six kinds of earthquakes. Numbers on the contour lines are the stress values. It manifested that there is no obvious change in the stress distribution with increasing of the seismic intensity.

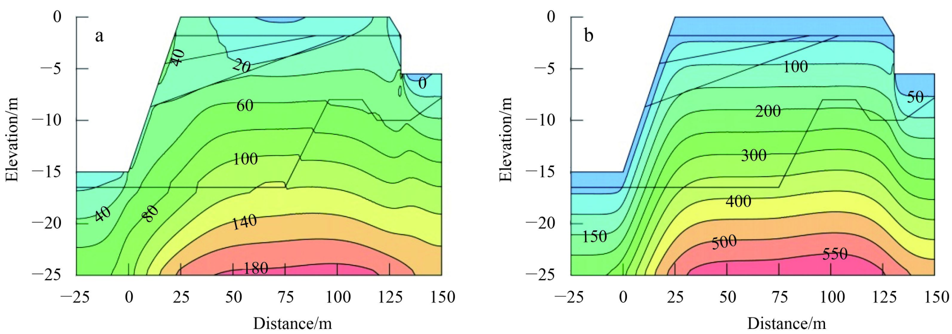

Fig. 3. Effective stress distribution under the self-gravity state. a. The effective stress distribution in *X*-direction, and b. the effective stress distribution in *Y*-direction. Numbers on the contour lines are the stress value (kPa).

The reef body has a well stability that probably attributes to the internal geotechnical structure characteristic under peak ground acceleration of 0.05 *g*. However, the stress field inside the reef body changes dramatically as the peak ground acceleration increase to 0.40 *g*, where the seismic intensity is greater than IX degree.

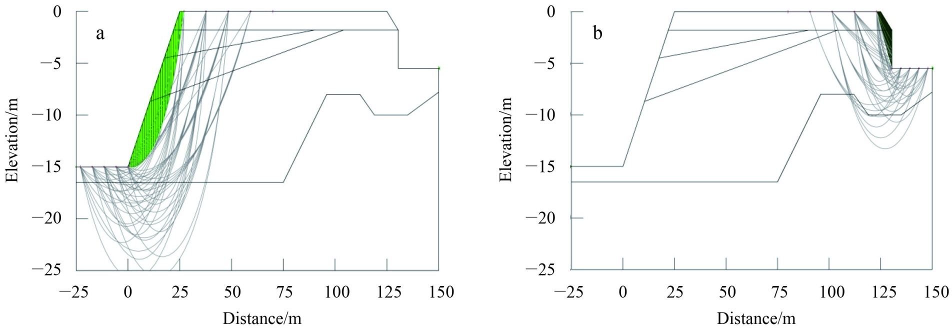

Fig. 4. Safety factor and critical slip surface of slopes under self-gravity state. a. The safety factor and the critical slip surface in left slope (F_S=1.977) and b. the safety factor and the critical slip surface in right slope (F_S=2.072). Gray lines are the multiple slip surfaces; green zone is the slip surface shading.

Table 2. Contrast between peak ground acceleration partition and seismic intensity (according to GB 18306-2001)

Peak ground acceleration	<0.05 *g*	0.05 *g*	0.10 *g*	0.15 *g*	0.20 *g*	0.30 *g*	≥0.35 *g*
Seismic intensity	<VI	VI	VII	VII	VIII	VIII	≥IX

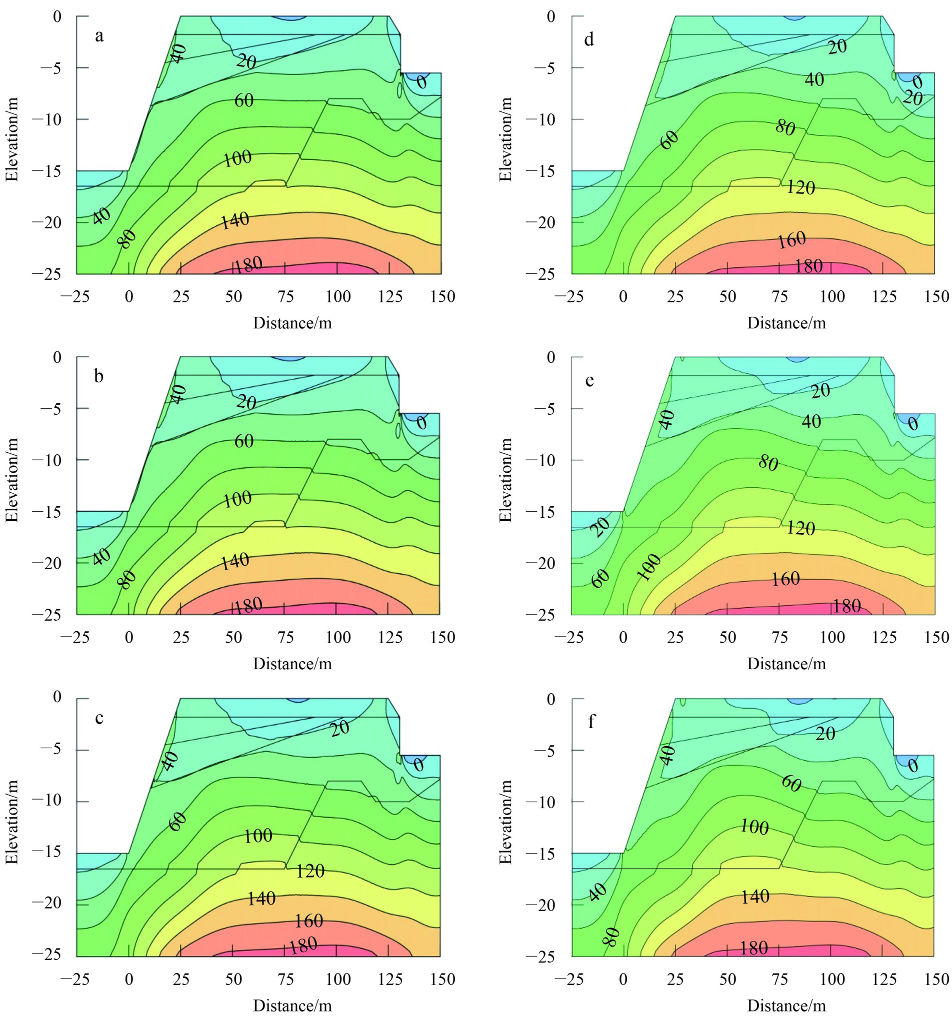

Fig. 5. Effective stress distribution of reef under different intensity earthquakes. a–f are peak acceleration of 0.05, 0.10, 0.15, 0.20, 0.30, and 0.40 *g*, respectively. Numbers on the contour lines are the stress value (kPa).

5.2.2 *Deformation of reef body*

The reef can produce different extents of a shape distortion under an earthquake. We stimulate the stress field of the reef model, as well as the reef deformation. The results imply that the change of the stress field is enhancing along with the seismic intensity increases. Furthermore, the deformation is also enlarging as the intensity increases (Fig. 6). It can be concluded from the figures that the reef body has a small-scale deformation when the seismic peak acceleration is less than 0.40 *g*, where some collapses may occur in slight slopes. When the peak acceleration is greater than 0.40 *g*, there will be a moderate-scale or a severe deformation of the whole reef body (Fig. 6b), reflecting a stability failure and slump under the shaking.

5.2.3 *Evaluation of single points in reef model*

According to the above results, the stress field and deforma-

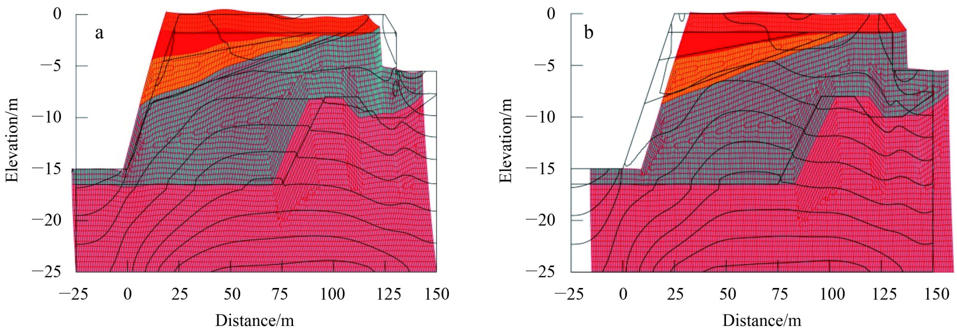

Fig. 6. Deformation of reef in different intensity earthquakes. a and b are peak acceleration of 0.05 *g* and 0.40 *g*, respectively. The red zone is the deformation shape.

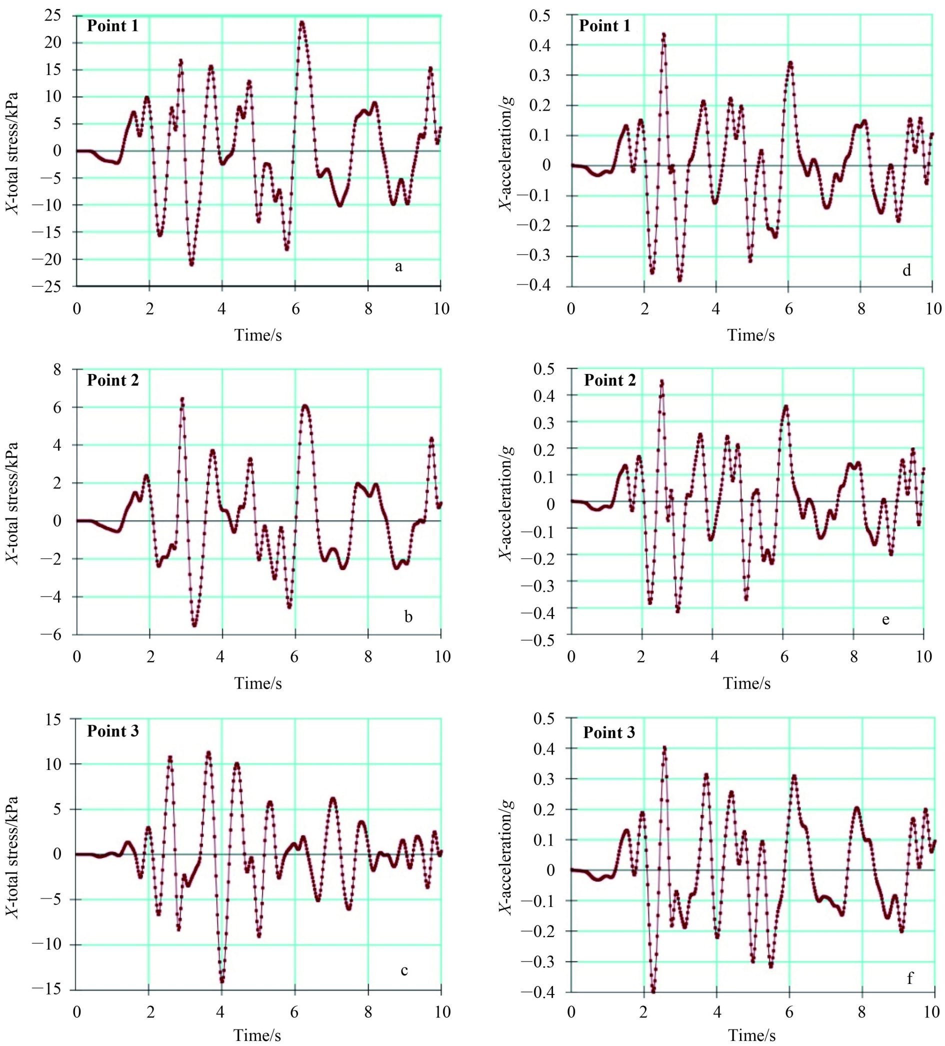

Fig. 7. Stress vs. time curves at three history points (a, b, and c) and acceleration vs. time curves at three history points (d, e and f).

tion of reef body change a lot when the seismic intensity is greater than IX degree (0.40 *g*). Owing to poor stability of the new top layer on model, we select three points of Layer 1 to do the further study (Fig. 1). In these three points, a serial of curves of the stress and acceleration are calculated and recorded along the shaking time during the modeling (Fig. 7). The results suggest that the stress at Point 2 changing smoothly along time, –6–8 kPa, the stress at Points 1 and 3 have some relative dramatic changes along the shaking time, with –25–25 kPa and –15–15 kPa, respectively. It indicates that there has been a greater stress field change in the shallow reef stratum. Also, there is a sharply change along the acceleration curve with time at all three points on the reef model, and it continued until the end of the earthquake. From the above results, we can draw a conclusion that the shallow layers are less steady under the earthquake, and the main factor of instability is not from the stress changes but the acceleration changes in the *X*-direction.

5.3 *Permanent deformation and stability after the earthquake*

To get a better understanding of the influence of earthquake on reefs, a permanent deformation and a stability analysis have also been carried out in this work. The slope safety factors have been calculated to assess the stability after the earthquake using the Newmark analysis method (Fig. 8). The calculation results

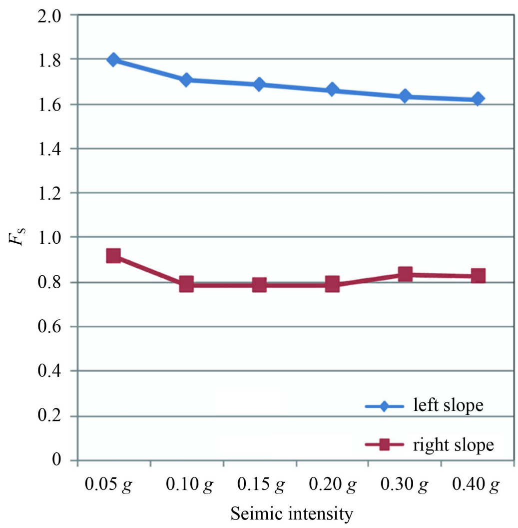

Fig. 8. Safety factor on both sides of slopes under different seismic intensities.

suggest that the safety factor of the larger left slope decreases linearly. However, the safety facoris greater than the critical value 1 all along, implying that the left slope has a good stability under a severe earthquake. In contrast, the safety factor of the right slope is dropping from 2.072 (self-gravity state) down to 0.916 (the smallest earthquake, where the seismic peak ground acceleration is only 0.05 *g*). Therefore, under an extremely small earthquake load, the slighter slope is relatively unsteady and easily accessed to unstable state. Furthermore, the analogue modeling results indicate that the new-generated shallow layer is easily broken and collapse under seismic action, which may change the reef shape and be recorded into the reef body.

For accurate quantitative description, the possible range of deformation and slump is also determined from the modeling. The location and size of the sliding surface after the earthquake are calculated from the simulation. As an example, Fig. 9 shows the location of right sliding-scale on reef under the seismic intensity of 0.40 *g*. The safety factor on this slope has plummeted since the earthquake starts (Fig. 10). In addition, based on these data, the minimum safety factor on the right slope is 0.832, the center location of the slip surface is 130.988, 1.665, and the sliding size is 7.183 m in radius (Table 3).

6 Conclusions

Integrating with the lithologic properties, the rock structure characteristic of reefs, and the drilling data, a simple reef model is established in the Nansha Islands. In this study, we analyzed the reef stability under the self-gravity state and six kinds of seismic intensities through comparing modeling experiments. To investigate the influence of earthquake on the reef, the safety factor and the deformation range of the reef slope are also calculated using the limit equilibrium slice method and the Newmark analysis method in geotechnical engineering. Simulating modeling experiments suggest that the reef body has a good stability and uniform stress field under minor and moderate earthquakes. It may sometimes occur little slump; coral reef may lose its stability and suffer extensive damaging under large quakes when the intensity is over 0.40 *g* acceleration; the main factor of losing stability is the acceleration change of particles in *X*-direction. Furthermore, according to the stability assessment after earthquake, the new-generated shallow layer on the reef is broken and an obvious deformation of shape in the shallow structure happened within the reef body when the earthquake occurred. Thus, the study of the engineering geological characteristics of reef and the relationships between earthquake and reef can have acted as an indication of neo-tectonic activity since Late Quaternary. The

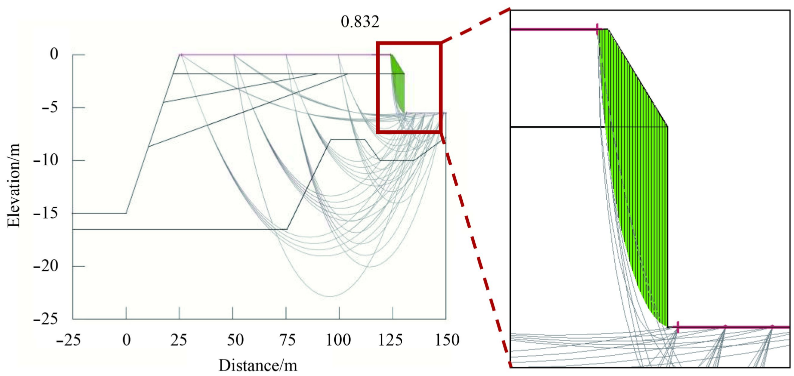

Fig. 9. Location of possible slip surface (green zone).

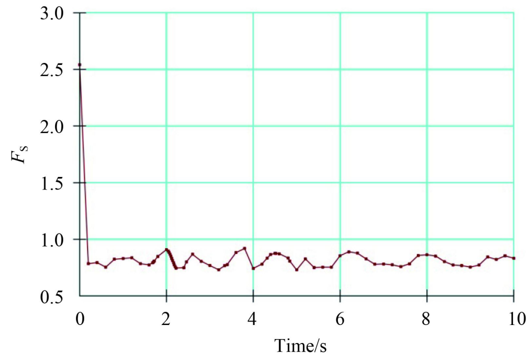

Fig. 10. Safety factor vs. time curve (0.40 *g*).

Table 3. Slice information of the possible slip surface

Item	Value	Item	Value
Safety factor	0.832	Slice width/m	0.25
Deformation/m^2	108.92	Mid-height/m	3.899
Velocity/m·s^{-1}	22.019	Base length/m	0.273
Average acceleration/m	0.985 1	Base angle/(°)	–23.489
Center *X*	130.988	Base normal force/kN	17.775
Center *Y*	1.665	Base normal stress/kPa	65.208
Radius/m	7.183	Top left coordinate/m	128, –0.982
Phi angle/(°)	30	Top right coordinate/m	128.25, –1.064
C (stress)/kPa	29	Bottom left coordinate/m	128, –4.868
f (force)/kN	7.905	Bottom right coordinate/m	128.25, –4.976

results also suggest that it is feasible to evaluate the stability of coral reef in the ocean by using testified methods in rock and mass engineering. The study here provides some reference data to assess reef structure assessment, which are the basic elements to analyze potential reef construction.

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