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Effect of rock mass characteristics of high rock slope on seismic stability

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Rock mass characteristics are the key internal factors for the stability of high rock slope. The lithological association of rock mass and its structural planes, such as dominant orientations, length, fracture aperture and stiffness attenuation, is investigated by exploration methods. Quantitative description is performed in terms of fracture geological and dynamic parameters to provide necessary basic data for the stability of rock slope. Based on rock mass with different geological characteristics on one site in the Songjiang area, Shanghai city, the fracture mechanism is studied using strength reduction finite element method. The different associations of the stiffness of rock mass and the dip of its structural planes are processed in dynamic state and its effects on the safety factor of rock slope are discussed.

Keywords: High rock slope, Rock mass structure, Lithological association, Structural planes, Seismic stability

Introduction

High slope engineering is an important problem in geotechnical engineering. Its stability problem is involved in mining engineering, road arid bridge engineering, water conservancy, structural engineering, etc. The damage induced by high slope is serious from the others; on the other hand, for the specific physical properties of rock mass, the damage induced by rock slope is more serious than that by soil slope. There are a large number of mountainous regions in China, especially in the western areas, with many large rock mass slopes alongside roads and railways, and the stability of the rock mass has a significant effect on the reliability and safety of these structures. Therefore, the stability of high rock slope becomes one of the most important problems in geotechnical engineering.

As we know, the factors that affect slope stability include internal factors (geomorphological characteristics, the properties of rock mass and soil, geological structure, rock structure and rock initial stress) and external factors (water, earthquake, rock weathering degree, load conditions and human activities). Internal factors control the effect on the stability of the slope and external factors induce the damage. Therefore, it is a key issue to clarify the internal factors by using effective methods.

As a case study, a high rock slope located in Songjiang area, Shanghai city is discussed. To clarify the key internal factors, a large number of advanced onsite investigations are used, such as digital photography technique, high density electrical tests and microtremor investigation, and a composite evaluation is obtained. Using numerical methods, the following problems are discussed: study on the influence on stability factors of rock slope, and the relationship between seismic loading and damages; study on the relationship between the weak layer thickness, angle and other factors and the seismic mass vibration parameters.

Tian Ma Hotel in Songjiang area, Shanghai city, China

Tian Ma Hotel is constructed in a deep excavated quarry located in the western of Shanghai city, Songjiang area, which is $\sim$30 km away from Shanghai city centre. It is constituted of two parts, which is a 19-story high building attached to the quarrying slope and a group of building on the ground. The quarry is at extended zone in exposed area of bedrock residual hill, and the stone mining was started from 1950 to 2000. Now it shows an oval shape, narrow in north–south and wide in east–west, and the slope angle is $\sim 80^\circ$. The area of the quarry is $\sim$36 800 m^2, with 80 m in depth, 240 m in length and 160 m in width. The average elevation of around ground is 2·80–3·50 m (Wusong elevation), the bottom of which is from $-48{\cdot}33$ to $-70{\cdot}53$ m.

Field investigation

The slope is divided into seven regions: eastern slope (2 zone) is trended to the northwest 338°, southwest tendency 248°, 78° dip, $\sim$150 m in length; northeast slope (3 zone) is trended to the northwest 280°, southwest tendency 190°, 76° dip, $\sim$155 m in length; northern slope (4 zone) is trended to the northeast 69°, southeast tendency 159°, 69° dip, 110 m in length; western slope (5 zone) is trended to true north 0°, due east tendency 90°, 73° dip, $\sim$270 m in length; southern slope (6 zone and 1 zone) is trended to the northeast 69°,

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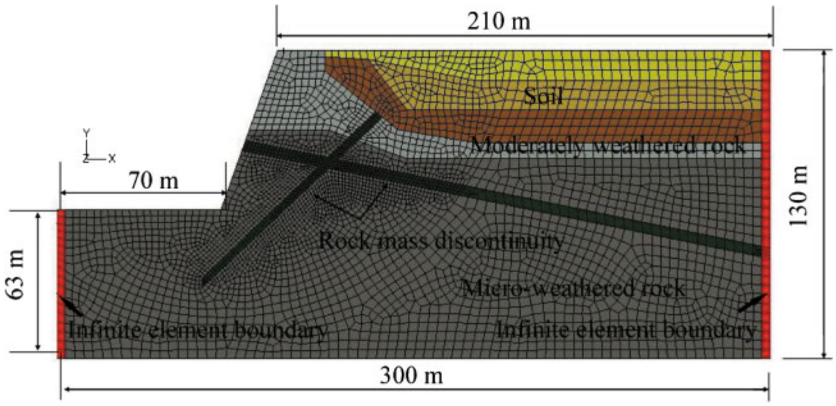


1 Simplified two-dimensional model

northwest tendency 339°, 71° dip, ~315 m in length. The rock stability that affected by geological conditions is investigated by exploration methods.

Geological characteristics of rock groups

The site is composed of Quaternary Period Holocene Seri upside terrestrial alluvial stratum Q_4^3, which is consisted of embankment, grey clay; Quaternary Period Holocene Seri midsection marine deposit stratum Q_4^2, which is consisted of dark green–grass yellow clay; J3h[3] andesite, with the degree of rock weathering from the top to the bottom is completely weathered andesite, strongly weathered andesite, weakly weathered andesite and faults. The depth of groundwater level is 1·9–6·4 m.

Using high density electrical field tests, the surface soil layer and the distribution of bedrock are investigated. The shear velocity of surface soil is 401–743 m s^{-1} and that of bedrock is 1687–2394 m s^{-1}. The investigation depth is ~40 m. It is shown that the depth of surface soil is gradually increased from 5 to 40 m from the edge of the slope to 80 m away.

Fractured rock mass

The geometric parameters of the exposed faults are obtained by line measurements and a geological compass. There are four exposed faults on the slope, and one of them is whole through the quarry.

The forward structure plane is one of the most important factors affecting the stability of the slope. Through digital photography tests and the bore data, the fracture zone within the rock slope, the presence of weak structure plane and its spatial distribution are evaluated.

Dynamic analysis of rock slope

Dynamic stability analytical method

With finite element method for infinite or semiinfinite domain problem, a certain width range is intercepted and imposed by artificial constraints on the boundary;[1–3] the effect of the far field is ignored. In this study, the finite element method–infinite element method is used to simulate the earthquake motions.

It has two steps to calculate the dynamic safety factors: in the first step, the initial stress generated by the gravity and earthquake motion is obtained by time history analysis;[4–6] in the second step, based on the initial stress, the dynamic safety factors using strength reduction method[7,8] are evaluated. The relationships among the rock mass strength parameters: cohesion c, friction angle φ and safety factor F_s, are as follows[9]

$$c_i = \frac{c}{F_s} \mathrm{tg}\varphi_i = \frac{\mathrm{tg}\varphi}{F_s} \tag{1}$$

where the elastic modulus E and Poisson's ratio λ are assumed to be constant respectively. Mohr–Coulomb model is used as the rock constitutive model.

Analytical model, parameters and loads

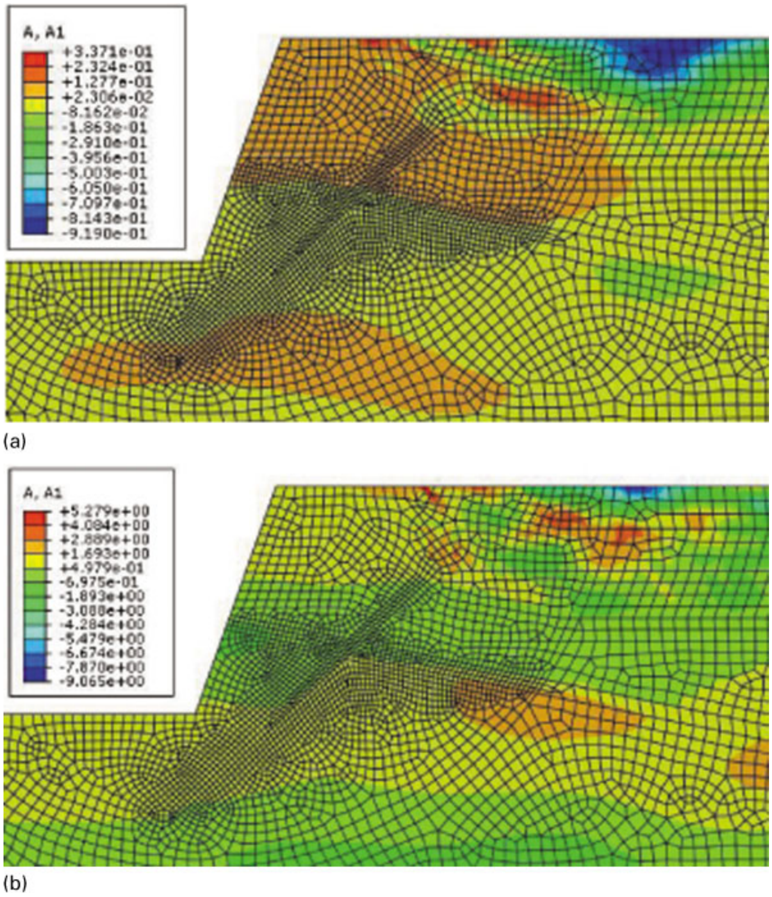
The simplified two-dimensional model is shown in Fig. 1. The rock mass and fractured rock mass are simulated as plane strain element. The boundary conditions are set as infinite element boundary. The total elements are 28 561, and nodes are 28 557.

The rock mass has obvious discontinuity with weak internal coupling strength bedding, schistose and joints and faults. The crack joints of rock mass in the research area are considerably developed, so that the parameters of the rock mass are greatly different from those of laboratory test results. According to the rock classification and the referential experience, the parameters of rock mass and the faults are shown in Table 1.

According to the seismic activity in the site, the earthquake waves on the bedrock are synthesised to 2% (great earthquake) and 63% (small earthquake) probabilities of exceedance in 50 years respectively. The

Table 1 Physical and mechanical properties of rock mass in research area

Name	Shear velocity V_s, m s^{-1}	Poisson's ratio μ	Density ρ, kN m^{-3}	Modulus E, GPa	Cohesion C, MPa	Friction angle φ, °
Embankment	123·8	0·47	19·2	0·088	0·018	16·0
Grey clay	143·8	0·47	19·0	0·119	0·015	15·0
Dark green–grass yellow clay	249·4	0·47	18·8	0·351	0·045	18·5
Weathered bedrock	2651	0·32	28·0	4·35	0·75	21·0
Weakly weathered bedrock	3009	0·32	28·0	5·5	1·12	21·0
Fault		0·3	25·6	0·5		



a small earthquake; *b* great earthquake

2 Acceleration distribution at top and bottom of slope

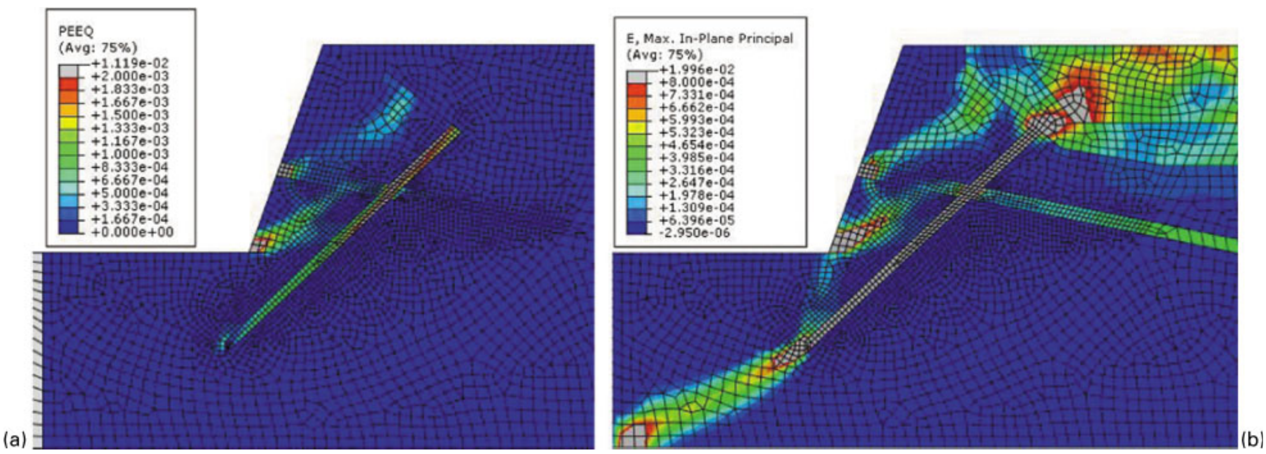
spectrum characteristics are 1·0–2·0 Hz, which are close to the frequency characteristics of the site.

Analytical results

During horizontal seismic load, the acceleration distribution of the slope is shown in Fig. 2. The acceleration response is amplified with the slope: the amplification is $\sim$2 times at the top of rock, and $\sim$5 times at the top of soil during small earthquake; $\sim$3 times at the top of rock, and $\sim$8 times at the top of soil during great earthquake. The dynamic response of soil is significantly amplified, and the amplification of rock slope is shown at the top of slope.

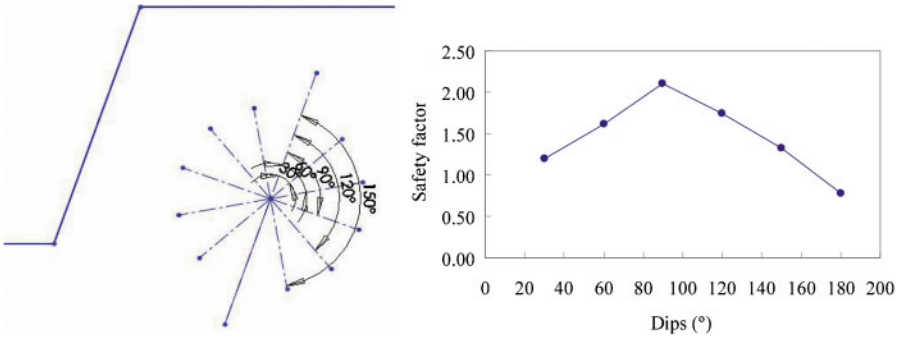
After several strength reductions, the limit steady state slope is reached determined by the non-convergence of the stress or displacement, where the safety factor is 1·50 during small earthquake and 1·0 during great earthquake. Figure 3 shows the strain distribution in the ultimate steady state of the slope, and it is considered that the generalised plastic strain zone is the sliding plane.

The effect of the dip of structure plane on dynamic safety factor is discussed by different dips during small



a small earthquake; *b* great earthquake

3 Strain distribution in ultimate steady state



4 Relationship between dip of structure plane and dynamic safety factors

earthquake motion, which are 30, 60, 90, 120, 150 and 180° respectively. Figure 4 shows the relationship between the dip of structure plane and the dynamic safety factors.

Conclusions

Based on a great deal of surface wave survey investigations and dynamic analysis, the seismic stability of high rock slope under earthquake ground motion is clarified and the dynamic evaluation of safety factors is discussed. The main results are as follows:

1. Using various kinds of exploration methods, the internal factors that affect slope stability including geomorphological characteristics, properties of rock mass and soil, geological structure, rock structure and structure plane are predominated.

2. Using strength reduction finite element method and stress superposition method, the critical failure surface due to earthquake is obtained.

3. The relationship between the dip of structure plane and dynamic safety factors is discussed.

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