Conceptualization and preliminary study of engineering disturbed rock dynamics

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Abstract Many large engineering projects, e.g., the Sichuan–Tibet Railway, inevitably cross the earthquake active areas and the geology complicated zones, facing the challenges of dynamic disturbances and disasters. In view of this, the conceptualization of engineering disturbed rock dynamics is proposed in this paper, aiming to systematically study the rock dynamic behavior and response subjected to engineering disturbances, to establish the 3D rock dynamic theory, and to develop the disaster prevention and control technical measures. The classification standards of rock loading states based on strain rate are summarized and analyzed. The engineering disturbed rock dynamics is defined as the theoretical and applied science of rock dynamic behaviors, dynamic

responses and their superposition caused by dynamic disturbances during engineering construction and operation periods. To achieve the goals of the proposed engineering disturbed rock dynamics, a combined methodology of theoretical analysis, laboratory experiment, numerical simulation and in situ tests is put forward. The associated research scopes are introduced, i.e., experimental and theoretical study of engineering disturbed rock dynamics, wave propagation, attenuation and superposition in rock masses, rock dynamic response of different loading conditions, dynamic response of engineering projects under construction disturbance and disaster mitigation techniques, and dynamic response of major engineering projects under operation disturbance and safety guarantee measures. Some theoretical, experimental and field preliminary studies were performed, including dynamic behavior of disturbed rock at varied depth and strain rates, dynamic response of rock mass subjected to blasting excavation disturbance and dynamic drilling disturbance, and disturbance of rock mass subjected to TBM excavation. Preliminary results showed that the rock masses are significantly disturbed by dynamic disturbances during construction and operation periods of engineering projects. The innovative conceptualization of engineering disturbed rock dynamics and the expected associated outcomes could facilitate establishing the 3D rock dynamic theory and offering theoretical fundamentals and technical guarantees for safety and reliability of the

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design, construction and operation of modern large engineering.

Keywords Engineering disturbed rock dynamics · Strain rate · 3D rock dynamics

1 Introduction

With the rapid development of human civilization since the industrial revolution, particularly, in the recent tens of years, a great number of large engineering projects have been constructed or under construction. The size and dimension of the engineering projects dramatically increase with time, and many new world records have been set. For example, the Golden Gate Bridge was both the longest (1280 m) and the tallest (227 m) suspension bridge in the world at the time of its opening in 1937, which has been declared as one of the Seven Wonders of the Modern World by the American Society of Civil Engineers. The Three Gorges Dam built in 2006 is the largest hydraulic engineering project in the world with a dam height of 181 m, length of 2335 m and width up to 115 m. The Gotthard Base Tunnel through the Alps opened in 2016 is the world's longest (57.09 km) railway and deepest (2300 m) traffic tunnel. During construction and operation, those engineering projects are subjected to dynamic disturbances, e.g., blasting and machine cutting during construction, and earthquakes and driving loads during operational period, and damage, failure or even disaster might occur. For example, the Sichuan–Tibet Railway inevitably crosses the earthquake active areas and the complex geological zones, naturally facing the challenges of dynamic disturbances and disasters. In fact, many disasters, e.g., tunnel rockburst, induced seismicity and sand liquefaction, are dynamic processes. Nevertheless, insufficient attentions have been paid to the influences of dynamic disturbances on engineering projects so far. The discrepancy between theoretical prediction (by approximating the dynamic problems as static ones) and actual performance of constructed engineering structures is usually tolerated. On the contrary, the standards and requirements for the engineering projects dramatically increase with the development of the society and technology, e.g., higher quality, higher reliability and longer life.

Therefore, theoretical study and analysis of dynamic behavior, responses and disasters should be of great importance to the construction and operation of the large engineering projects.

In fact, during construction and operation of major engineering projects, e.g., civil engineering, mining engineering, hydraulic engineering, bridge engineering and petroleum engineering, the structures built in or on rock mass not only bear the complex in situ conditions, e.g., stress, seepage, faulting, thermal and chemical coupling, but also often encounter a variety of dynamic disturbances during engineering construction and operation periods (e.g., blasting, TBM excavation, hydraulic fracturing, geological drilling and rockburst during engineering construction, natural earthquakes, driving loads, sequential explosions or even military attacks during engineering operation), whose strain rate is over the threshold value (Meyers 1994; Zhang and Zhao 2014a). Besides, the major engineering projects after construction are no longer built in or on the natural intact surrounding rocks, but located in or on the disturbed and deteriorated rock masses (Li et al. 2013a, b; Deng et al. 2014; Liu et al. 2018). As a result, the mechanical responses of major engineering become more complicated due to the coupled impact of the dynamic disturbances and in situ conditions. However, the coupled influence of the dynamic disturbance and in situ conditions on the safety and stability of engineering structures built in or on rock masses was often neglected in previous design, analysis and research of engineering structures. Therefore, understanding the rock dynamic behavior subjected to engineering disturbances is essential to guarantee the reliability and safety of engineering projects during construction and operation periods.

However, discrepancy often exists between the theoretical prediction using conventional rock mechanics and the actual performance of major engineering projects during construction and operation periods, and disasters might occur from time to time. Except the insufficient attentions paid to the dynamic disturbances, this is mainly because the rock dynamics theories are still at its infancy in spite of extensive previous efforts devoted to rock dynamics. Besides, there exists no laboratory dynamic apparatus that could completely replicate the in situ conditions of rock, e.g., the true triaxial synchronous impact test

device, and no systematic field tests of engineering disturbed rock dynamics have been conducted.

Some efforts have been devoted to theoretically or empirically analyzing rock dynamic behavior. By combining the effective bulk modulus expression (Budiansky and O'connell 1976) with the fragment size equation (Grady 1983), Taylor et al. (1986) developed a damage growth model to examine the dynamic fracture behavior of brittle rock under dynamic loading. In this model, the dynamic fracture process in rock is treated as a continuous accrual of damage, which is attributed to the microcracking in the rock medium under dynamic loading conditions. Xie and Sanderson (1986) derived a formula to describe the influence of crack propagation on the dynamic stress intensity factor and crack velocity using fractal theory, which are found to be dependent on fractal dimension, the fractal kinking angle of crack extension path as well as microstructure. Yang et al. (1996) derived a constitutive model to characterize blast-induced damage in rocks, where the initiation and development of dynamic damage are controlled by extensional strain. Zhao (2000) examined the applicability of the Mohr–Coulomb and the Hoek–Brown criteria to rock strength under dynamic loading conditions. The results indicated that the Mohr–Coulomb criterion is capable of only characterizing dynamic strength of rocks under uniaxial compression or under low confining stress, while the Hoek–Brown criterion can represent dynamic triaxial strength of rock materials under both low and high confining pressures. By incorporating crack growth dynamics, Bhat et al. (2012) extended the physical model developed by Ashby and Sammis (1990) to predict dynamic damage evolution in brittle rocks over a wide range of loading rates. Recently, considering that the dynamic disturbances, e.g., transient unloading, blasting and earthquakes, may affect the quality of rock mass, Hoek and Brown (2019) modified the generalized Hoek–Brown criterion by adding a disturbance factor. In addition, theoretical investigations of stress wave propagation and attenuation in rock masses have also been extensively carried out in recent years (Chai et al. 2017; Fan et al. 2013; Li et al. 2010a, 2013a, b 2015, 2019; Zhou et al. 2017; Zhu et al. 2011; Zhu and Zhao 2013). However, no systematic and universal theoretical framework for rock dynamic has been established so far. In spite of some dynamic damage models, most of which are in fact quasi-static ones, the

universal constitutive laws and failure criteria for rocks under dynamic loadings are still rarely developed. The characteristics of actual engineering projects, e.g., the stochastic and irregular stress waves, dynamic thermal–hydraulic–mechanical (THM) coupling and discontinuous nature of rock mass, were usually neglected in previous studies.

Extensive experimental studies of rock behavior subjected to dynamic loadings have been conducted in the past decades. Since Kumar (1968) first introduced the split Hopkinson pressure bar (SHPB) device to perform rock dynamic experiments in 1968, the SHPB has become one of the most widely utilized technique for investigating the mechanical and fracture behavior of rocks under impact with high strain rate (Doan and Gary 2009; Frew et al. 2001; Li et al. 2005; Lindholm et al. 1974; Olsson 1991; Zhang and Zhao 2014b; Zhu et al. 2016; Zhou et al. 2018; Zhu et al. 2018; Gong et al. 2019). Li et al. (2005) investigated the mechanical properties of the Bukit Timah granite at a strain rate of 10^1 s^{-1} with a large-diameter (75 mm) SHPB device. It is found that the dynamic strength of the granite is proportional to the cube root of the strain rate, while the energy consumption increases linearly with strain rate. Li et al. (2008) conducted dynamic loading experiments on siltstone with static confinements using a modified SHPB equipment, showing that the rock strength under coupling loads is higher than their corresponding strength under static or dynamic loading conditions. Yuan et al. (2011) carried out impact tests on Westerly granite under confined loading conditions, and reported that a strain rate over 300 s^{-1} is necessary to convert the Westerly granite from sparse fracture to pervasive pulverization under dynamic impact. Recently, Liu et al. (2019) developed a triaxial Hopkinson bar where multiaxial static confinement and one-direction impact could be realized. A preliminary test showed that the strength of sandstone decreases with the increase of the maximum principle stress along the impact direction, while it increases with increasing lateral intermediate and minimum principal stress. In addition to the SHPB, experimental studies of rock dynamic behavior have also been conducted with the other laboratory means, e.g., the hydraulic servo-control device (Zhao et al. 1999), the hammer-drop apparatus (Li et al. 2001), the drop weight testing machine (Reddish et al. 2005; Whittles et al. 2006) and the planar impact facility (Ahrens and Rubin 1993). However, the existing rock

dynamic laboratory apparatuses could not mimic the in situ dynamic loading conditions during engineering construction and operation, e.g., multiaxial synchronous dynamic loading. Besides, the repeatability and accuracy of the dynamic loading could not be guaranteed.

In addition to theoretical and experimental efforts, field investigations of rock dynamics have been performed. With the analysis of in situ blasting testing results, Dowding (1985) indicated that the peak particle velocity is the most representative parameter to describe the dynamic response of the tunnels and ground motions. Hao et al. (2001) studied the influences of rock joints on blast-induced wave propagation at a jointed rock site, and noted that rock joints such as joint number and joint inclination angle have significant effects on the propagation characteristics of blast-induced shock waves. A large-scale decoupled underground explosion test with 10 tons of TNT was conducted in Älvdalen, Sweden, and the dynamic behavior of surrounding tunnel and rock masses as well as ground motions was studied (Chong et al. 2002; Deng et al. 2015). Based on the geological and geophysical data as well as the field monitoring, Kim et al. (2018) concluded that the 2017 Mw 5.4 Pohang earthquake in South Korea was induced by the dynamic disturbance of hydraulic fracturing in the enhanced geothermal system. After analyzing the strong ground motion data recorded by 22 accelerometers during the Van earthquake (Turkey) 2011, Beyhan et al. (2019) pointed out that the strongest ground shaking occurred around the location of the large slip asperities. However, previous studies are isolated and segmentary, and no systematic investigation on the dynamic behavior and response of rocks during construction and operation of major engineering projects has been performed. In addition, the in situ strain rate, a key parameter for rock dynamic behavior, and the dynamic disturbed range during engineering construction and operation, have not been well investigated so far.

To systematically study the rock dynamic behavior subjected to engineering disturbances, to establish the rock dynamic theories and testing devices considering dynamic disturbances, and to develop the disaster prevention and control measures during construction and operation of engineering projects, the conceptualization of engineering disturbed rock dynamics was introduced, and preliminary studies were performed in

this paper. Firstly, the conceptualization of engineering disturbed rock dynamics as well as the associated focuses, objectives and research methodology was introduced, after summarizing classification standards of rock loading states based on strain rate and proposing the threshold strain rate. Subsequently, the research scopes of engineering disturbed rock dynamics were presented. Finally, some preliminary studies of engineering disturbed rock dynamics were briefly demonstrated. The innovative conceptualization and the expected associated outcomes could facilitate establishing the 3D rock dynamic theory and offering theoretical fundamentals and technical guarantees for safety and reliability of the design, construction and operation of modern large engineering.

2 Dynamic response of rock

Rock deformation and failure are time-dependent dynamic processes, ranging from long-term creep (rheological) to instantaneous fracturing. Therefore, rock mechanics can be divided into rock statics and rock dynamics in a broad sense. In spite of many parameters to describe the dynamic response of rock, e.g., particle velocity, particle acceleration and stress, strain rate or loading rate is usually used to distinguish rock statics and rock dynamics. However, there has been no consensus on the rate boundary between rock statics and rock dynamics so far. Moreover, according to the strain rate or loading mode, rock dynamics is often divided into quasi-dynamic, dynamic and super dynamic states (Li 2014; Nemat-Nasser 2000; Sharpe 2008; Zhang and Zhao 2014b). Table 1 summarizes some classification standards of rock loading states based on strain rate, where strain rate regimes of creep, static/quasi-static and dynamic (including quasi-dynamic, dynamic and super dynamic) are classified. Notably, strain rate ranges, i.e., intermediate strain rate, high strain rate and very high strain rate, are adopted to characterize dynamic mechanical states. It can be found that most scholars viewed 10^{-5} s^{-1} as the critical strain rate between creep and static loadings. Nevertheless, the strain rate boundary between static and quasi-dynamic is unclear, ranging from 10^{-6} to 10^0 s^{-1} . In addition, there is no recognized strain rate to distinguish quasi-dynamic and dynamic loading states.

Table 1 Classification of loading states based on strain rate

Sources	Strain-rate regimes (s^{-1}) ^a				
	Creep	Static/ Quasi-static	Quasi-dynamic/ISR	Dynamic/ HSR Super-	-dynamic/ Impact/VHSR
Kumar (1968)	$< 10^{-6}$	10^6-10^2	–	10^2-10^3	–
Logan and Handin (1970)	–	10^5-10^{-2}	$10^{-2}-10^2$	$> 10^2$	–
Wang (1982)	$< 10^{-5}$	$10^{-5}-10^{-1}$	$10^{-1}-10^1$	10^2-10^4	10^4-10^8
Curran et al. (1987)	$< 10^4$	–	$10^{-4}-10^3$	–	10^4-10^6
Olsson (1991)	10^{-14}	$< 10^{-6}$	$10^{-6}-10^3$	$> 10^3$	10^8
Nemat-Nasser (2000)	$< 10^{-5}$	$10^{-5}-10^{-1}$	$10^{-1}-10^2$	10^2-10^4	$> 10^4$
Field et al. (2004)	$10^{-8}-10^{-6}$	$10^{-4}-10^0$	–	10^0-10^4	10^4-10^8
Cai et al. (2007)	$< 10^{-7}$	10^7-10^4	$10^{-4}-10^0$	10^0-10^3	10^3-10^5
Sharpe (2008)	$< 10^{-6}$	$10^{-6}-10^{-3}$	$10^{-3}-10^2$	10^2-10^4	$> 10^4$
Jiang and Vecchio (2009)	–	$< 10^0$	10^0-10^1	10^2-10^3	$> 10^4$
Huang (2011)	$< 10^{-5}$	$10^{-5}-10^{-1}$	–	$10^{-1}-10^4$	$> 10^5$
Li (2014)	$< 10^{-5}$	$10^{-5}-10^{-1}$	$10^{-1}-10^1$	10^1-10^3	$> 10^4$
Zhang and Zhao (2014a, b)	$10^{-8}-10^{-5}$	$10^{-5}-10^{-1}$	$10^{-1}-10^1$	10^1-10^4	10^4-10^6
Li et al. (2017)	$10^{-7}-10^{-5}$	$10^{-5}-10^{-2}$	$10^{-1}-10^1$	10^1-10^3	10^3-10^5

^aISR intermediate strain rate, HSR high strain rate, VHSR very high strain rate

To avoid confusion due to inconsistent classification standards and definitely distinguish loading states, it is proposed in this paper to classify the loading states into static and dynamic ones based on the strain rate effect and experimental measurements in literatures (see Table 2). The strain rate of $10^{-4} s^{-1}$ is the threshold between static and dynamic loading states, because many previous experimental results indicated that strain rate effect is negligible when the strain rate is below $10^{-4} s^{-1}$, whereas, above which, the strain rate effect on the mechanical properties of rock is significant (Cai et al. 2007; Frew et al. 2001; Hentz et al. 2004; Kumar 1968; Lindholm et al. 1974; Logan and Handin 1970; Malvar and Crawford 1998; Olsson 1991; Wang and Tonon 2011; Zhang and Zhao 2014b; Zhao et al. 1999). When the strain rate exceeds

$10^1 s^{-1}$, the strain rate effect is significantly higher (even more than ten times) than that under a strain rate between $10^{-4} s^{-1}$ and $10^1 s^{-1}$. And hence, the dynamic loading state is further divided into two sub-regions, i.e., intermediate strain rate ($10^{-4}-10^1 s^{-1}$) loading state and high strain rate ($> 10^1 s^{-1}$) loading state. Besides, the typical laboratory loading devices applied to realize the corresponding strain rates are also illustrated in Table 2. In general, a conventional servo-hydraulic machine with high stiffness can load samples at a strain rate up to $10^{-1} s^{-1}$. A specially designed gas-driven fast loading equipment and drop weight can achieve the strain rate at the order of $10^{-1} s^{-1}$ and $10^1 s^{-1}$, respectively. Regarding the strain rate at the order of $10^1-10^3 s^{-1}$, the most widely applied technique is the SHPB. Strain

Table 2 Classification of loading states and strain rate regimes with associated laboratory experimental instruments

Loading types	Static	Dynamic			
Strain rate regimes	Low strain rate	Intermediate strain rate		High strain rate	
Strain rate (s^{-1})	$< 10^{-4}$	$10^{-4}-10^1$		$> 10^1$	
Specific strain rate (s^{-1})	$< 10^{-4}$	$10^{-4}-10^{-1}$	$10^{-1}-10^1$	10^1-10^3	$> 10^3$
Associated device	Specialized hydraulic machine	Servo-hydraulic machine	Drop weight	SHPB	Light gas gun

rate of 10^3 s^{-1} or higher could be achieved by the plate impact tests launched by the light gas gun.

3 Conceptualization and research scopes of engineering disturbed rock dynamics

3.1 Conceptualization

Herein, the engineering disturbed rock dynamics is proposed. It is defined as the theoretical and applied science of rock dynamic behaviors, dynamic responses and their superposition caused by dynamic disturbances during construction and operation of major engineering projects.

The engineering disturbed rock dynamics addresses aspects including the theories, mechanisms, testing apparatus development, laboratory and field tests, and technical measures. Theoretical issues include rock dynamic responses and mechanical behavior subjected to the engineering disturbances during the periods of construction and operation, mechanisms of dynamic disasters subjected to engineering disturbances with various dynamic loading types, the interaction of wave propagation and dynamic response and behavior of fractured rock masses, and eventually the 3D rock dynamics theories considering the effect of engineering disturbance. In addition to fundamental theoretical studies, the engineering disturbed rock dynamics is dedicated to building the rock dynamic testing devices that could model the coupled effect of engineering disturbance and in situ conditions such as true triaxial synchronized electromagnetic impact testing device, carrying out laboratory and field tests with a focus on different loading conditions and strain rate effect, and setting up the technical measures for mitigation and prevention of dynamic disasters during construction and operation of rock structures.

Through the aforementioned theoretical, experimental and technical studies on the engineering disturbed rock dynamics, it is expected that the following goals would be achieved: (1) to develop a series of innovative 3D rock dynamics testing devices; (2) to establish the theories of engineering disturbed 3D rock dynamics; (3) to develop a disaster mitigation and safety guarantee system for the construction and operation of major rock engineering; and (4) to propose and update design standards and guidelines

of major rock engineering with the consideration of dynamic engineering disturbances.

To achieve these goals, an integrated research methodology of theoretical analysis, experimental testing, numerical modelling and in situ monitoring as well as technique development (as shown in Fig. 1) will be applied.

3.2 Research scopes

There are five research scopes for the proposed engineering disturbed rock dynamics.

3.2.1 *Experimental and theoretical study of engineering disturbed rock dynamics*

Using the laboratory apparatuses including the true triaxial synchronous electromagnetic impact testing device, dynamic laboratory tests are to be conducted to investigate the mechanical behavior, damage evolution, fracture propagation and failure mechanism of rocks under different testing conditions, e.g., dynamic loading state (uniaxial, biaxial and triaxial synchronous impact), pre-applied static loading condition (1D, 2D and 3D), thermal condition (temperature), hydraulic state (pore pressure, seepage) and dynamic effect (strain rate).

Based on the laboratory measurements, theoretical studies will also be performed. From micro, meso and macro views, the constitutive models, strength and failure criteria of intact rock considering the dynamic disturbances are to be built, and the 3D dynamic damage and fracture theory will be established. The THM coupled rock dynamics theories will be developed. In addition, by analyzing the stress distribution and concentration of discontinuous rock with pores, cracks and fractures under dynamic disturbances, the strain rate effect of 3D fracture initiation, propagation and termination will be determined.

3.2.2 *Wave propagation, attenuation and superposition in rock masses*

By investigating wave propagation through intact rock, the effects of disturbance type, wave frequency, duration and amplitude on wave propagation are to be determined. Wave propagation through discontinuous rock with pores, cracks and joints will be studied, where the rock heterogeneity and anisotropy and

Fig. 1 The flowchart of the step-by-step research scopes

damage evolution will be considered. In addition, through analyzing the interaction of stress wave with rock discontinuities such as joints and faults, the wave attenuation and superposition at discontinuities will be studied.

3.2.3 Rock dynamic response under different loading conditions

The dynamic disturbances are to be simulated in laboratory, and the dynamic behavior and responses of rock will be studied. The loading types include hydraulic fracturing, TMB excavation, blasting, mining excavation, underground reservoir drainage, driving load, etc. The dynamic behavior and responses of rock include damage evolution, crack propagation, failure mechanism, fatigue fracturing, induced seismicity, rock cutting, rockburst, etc.

3.2.4 Dynamic response of major engineering projects under construction disturbance and disaster mitigation techniques

Construction of major engineering projects, e.g., mining, resource and energy engineering, bridge and tunnel engineering, hydraulic engineering, underground energy storage, is accompanied with dynamic

disturbances, e.g., blasting vibration, TBM excavation and drainage cyclic impact. Due to those dynamic disturbances, dynamic disasters such as rockburst, landslide, dam failure and induced seismicity often occur. Therefore, the dynamic responses of rock masses during construction period will be studied, aiming to understand the damage, fracture, failure and instability of rock and rock structures subjected to dynamic disturbances, and eventually to develop the disaster mitigation and prevention technique system during construction period.

3.2.5 Dynamic response of major engineering projects under operation disturbance and safety guarantee techniques

Engineering projects (mining engineering, bridge and tunneling engineering, hydraulic engineering and energy engineering, etc.) during operational period often bear dynamic disturbances, e.g., natural earthquake, nearby blasting, driving load, landslide impact. And those engineering projects are liable to suffer from various dynamic disasters. Therefore, it is proposed to study the dynamic responses, damage, fatigue and failure of rock and rock structures subjected to dynamic disturbances during engineering operation period. And the safety guarantee techniques

of engineering projects under operation need to be established.

4 Preliminary studies

To examine the effects of dynamic disturbances on rock and rock structures during engineering construction and operation, and to initiate the efforts for investigating engineering disturbed rock dynamics, we carried out some preliminary studies.

4.1 Dynamic behavior of disturbed rock at varied depth and strain rate

The mechanical properties of in situ rocks are likely influenced by the in situ stress together with the disturbed stress induced by the drilling, blasting, rockburst and earthquake (Li et al. 2010b; Liu et al.

Fig. 2 The relationship between dynamic strength and strain rate of Jinping marble at varied depths: **a** 0 m, 100 m, 300 m and 600 m; and **b** 600 m, 700 m, 900 m, 1200 m, 1500 m and 1800 m (adapted from Tan 2019)

Fig. 3 The relationship between dynamic strength and depth of Jinping marble under different strain rates (adapted from Tan 2019)

2019). To investigate the dynamic behavior of rock at varied depth after dynamic disturbances, laboratory tests using the SHPB were performed. Marble specimens are cylinders with the height of 40 mm and diameter of 50 mm from rock cores at varied depth in Jinping. Note that the artificial disturbance generated during rock core sampling is ignored in this study. The applied axial static stresses simulating the vertical in situ stress are 0 MPa, 5.3 MPa, 15.9 MPa, 31.8 MPa, 37.1 MPa, 47.7 MPa, 63.6 MPa, 79.5 MPa and 95.4 MPa for corresponding buried depths of 0 m, 100 m, 300 m, 600 m, 700 m, 900 m, 1200 m, 1500 m and 1800 m, respectively. Here, the bulk density of disturbed rock is 26.5 kN/m^3 , and the stress concentration factor for disturbed rock considering excavated tunnel shape is 2. Note that the preset horizontal in situ stress is ignored. The strain rate in this study is in the order of 10^1 – 10^2 s^{-1} .

Figure 2 shows the relationship between dynamic strength and strain rate of Jinping marble at varied depths. It is demonstrated that the dynamic strength is largely influenced by the strain rate. Based on the regression analysis, a positive linear relationship between dynamic strength and strain rate is found. This is because with increasing strain rate, more micro-cracks are generated in the specimen in the failure process (Fuenkajorn et al. 2012). It means that more external force work is consumed during the failure process of Jinping marble, leading to an increasing tendency of dynamic strength of Jinping marble.

Figure 3 illustrates the dependence of dynamic strength on buried depth of Jinping marble under different strain rates. It is revealed that the dynamic strength of Jinping marble shows a parabolic tendency

Fig. 4 Construction site of the ventilation shaft of Maluanshan Tunnel in Shenzhen, China

as the depth increases from 0 to 1800 m. With increasing buried depth, the dynamic strength increases firstly, reaches the maximum value at the depth of 600 m and then decreases. Additionally, the sensitivity of strain rate dependency on dynamic strength decreases as the depth increases.

4.2 Dynamic response of rock mass subjected to blasting excavation disturbance

The blasting vibration can cause damage, degradation and even instability of the rock mass and structure. Therefore, field dynamic tests were carried out during the excavation of a ventilation shaft with drilling and blasting method. The ventilation shaft is a part of the Maluanshan tunnel located in Shenzhen, China, which has a design depth of 193 m and excavation diameter of 16.7 m, where the formations are strongly, moderately and slightly weathered granite, as shown in Fig. 4. Two boreholes were drilled and ground vibration gauges and buried strain gauges were installed as shown in Fig. 5. When the ventilation shaft was excavated to the depth of 40 m, the millisecond blasting with emulsion explosive of

Fig. 5 Schematic diagram of measuring arrangement during blasting excavation of the ventilation shaft of Maluanshan Tunnel in Shenzhen, China

65 kg was conducted, and the dynamic responses of surrounding rock, i.e., peak particle velocity (PPV) and strain, were recorded.

Figure 6 shows the recorded PPV along the horizontal and vertical directions in the surrounding rock mass during blasting. Measured results showed that the PPV decreases as the distance from the blasting source increases. And the PPV along the vertical direction is higher than that along the horizontal direction, given similar distance from the blasting source. This is because the measuring points p_1 – p_5 are located in the moderately weathered granite stratum, while the measuring points p_c , p_d and p_e were located in the slightly weathered granite stratum. And wave attenuation is more significant in poorer rock mass.

The dynamic strain of the rock was also recorded, and the strain rate was derived through its derivation with respect to time. Figure 7 shows the strain rate in the rock mass along the horizontal and vertical directions. It can be seen that the magnitude of the strain rate (at the order of 10^0 s^{-1}) is far beyond the threshold of 10^{-4} s^{-1} , indicating that the range of dynamically disturbed surrounding rock mass could be

Fig. 6 The PPV recorded in the rock mass: **a** along the horizontal direction; and **b** along the vertical direction

hundreds of meters. And the strain rate decreases as the distance from the blasting source increases. The measured results indicate that the surrounding rock mass is suffered from dynamic disturbance, and the strain rate effect should be taken into account when evaluating the dynamic response and stability of surrounding rock.

4.3 Disturbance of rock mass subjected to TBM excavation

Under high in situ stress in deep Earth, the dynamic disturbance from mechanical excavation could lead to the deterioration and damage of the surrounding rock mass. To examine the influence of dynamic disturbance on surrounding rock mass, four boreholes at

Fig. 7 The strain rate in the rock mass: **a** along the horizontal direction; and **b** along the vertical direction

varied depths were drilled in the transportation tunnel of the Jinping Phase II hydraulic project.

To evaluate the degradation of surrounding rock masses of the transportation tunnel, the in situ acoustic wave tests along four boreholes were performed, as the wave velocity could reflect the damage degree of surrounding rock mass (Zou et al. 2016). The measured data were plotted in Fig. 8. The P-wave velocity range for each borehole at the depth of 100 m, 1000 m, 1800 m and 2400 m is 3817–6667 m/s, 3876–5952 m/s, 3333–6410 m/s and 3185–6667 m/s, respectively. The P-wave velocity increases with increasing distance from the tunnel surface, indicating that dynamic disturbance induced damage is more severe in surrounding rock closer to the tunnel surface.

Fig. 8 Scatter diagram of the P-wave velocity along the borehole at varied depths (adapted from Tan 2019)

Fig. 9 Schematic diagram of measuring set-up during drilling in Bijie

4.4 Dynamic response of rock mass subjected to dynamic drilling disturbance

The drilling vibration can cause dynamic response and damage of the rock mass. Drilling was conducted in Bijie, China, where the rock formations are mainly microcrystalline limestone and mudstone. A monitoring system composed of 14 measuring points was set up to monitor the vibration of rock mass during drilling, as shown in Fig. 9. 12 vibration gauges were installed in each measuring point. The rig drilled with a velocity of 11.26 m/h, and the drill diameter is 16.8 cm.

Figures 10 and 11 show the recorded PPV and strain rate in the rock mass as a function of the distance from the drill pipe axis during drilling in Bijie. It can be seen that both the PPV and strain rate decrease as

Fig. 10 The measured PPV in the rock mass as a function of the distance from the drill pipe axis during drilling in Bijie

the distance from the pipe axis increases. When the distance from the drill pipe axis is about 75 m, the strain rate in rock mass reduced to about 10^{-3} s^{-1} . As the threshold strain rate of rock dynamics is 10^{-4} s^{-1} , the dynamic disturbed diameter during drilling is beyond 75 m.

5 Summary and way forward

To systematically study the rock dynamic behavior and response subjected to engineering disturbances, to establish the 3D rock dynamic theory, and to develop the disaster prevention and control measures, the conceptualization of engineering disturbed rock dynamics was introduced and preliminary studies

Fig. 11 The strain rate in the rock mass as a function of the distance from the drill pipe axis during drilling in Bijie

were performed in this paper. The classification standards of rock loading states based on strain rate was summarized, following which, the strain rate of 10^{-4} s^{-1} was proposed as the threshold between static and dynamic loading state.

The conceptualization of engineering disturbed rock dynamics as well as the associated focuses, objectives and research methodology were introduced. According to the threshold strain rate of 10^{-4} s^{-1} , engineering projects are commonly subjected to dynamic disturbances during construction and operation periods. The engineering projects after bearing dynamic disturbances during construction are no longer built in or on the natural intact surrounding rocks, but located in or on disturbed or damaged rock masses. Therefore, dynamic disturbances are critical to the reliability and safety of major engineering projects. However, the impact of dynamic disturbance on the safety and stability of major projects was usually neglected. The main reasons include the lack of established theoretical system of rock dynamics which is commonly recognized, the insufficiency of laboratory dynamic tests which could replicate in situ dynamic loading condition, and the deficiency of systematical field tests which, in particular, include field strain rate tests during construction and operation periods. In view of this, the conceptualization of engineering disturbed rock dynamics was proposed. It is defined as the theoretical and applied science of rock dynamic behaviors, dynamic responses and their

superposition caused by dynamic disturbances during engineering construction and operation periods.

To achieve the goals of the proposed engineering disturbed rock dynamics, a combined methodology of theoretical analysis, laboratory experiment, numerical simulation and in situ tests is employed. The associated research scopes were introduced, i.e., experimental and theoretical study of engineering disturbed rock dynamics, wave propagation, attenuation and superposition in rock masses, rock dynamic response of different loading conditions, dynamic response of major engineering projects under construction disturbance and disaster mitigation techniques, and dynamic response of major engineering projects under operation disturbance and safety guarantee measures.

Some theoretical, experimental and in situ preliminary studies, i.e., dynamic behavior of disturbed rock at varied depth and strain rate, dynamic response of rock mass subjected to blasting excavation disturbance and dynamic drilling disturbance, and disturbance of rock mass subjected to TBM excavation. Results showed that the rock masses are significantly disturbed by dynamic disturbances during construction and operation periods of engineering projects.

This paper proposes the conceptualization of engineering disturbed rock dynamics. In spite of previous studies by a great number of researchers and preliminary works in this paper, further efforts from the community of rock mechanics and rock engineering, in particular, rock dynamics, are needed. First, innovative laboratory testing means (e.g., the true triaxial synchronous impact test device) that could mimic the in situ dynamic disturbances needs to be developed. Efforts and input from mechanical engineering, electronic engineering, optical engineering, etc., are needed. Second, the 3D rock dynamic theories considering the engineering disturbances are to be established. In addition to efforts from rock mechanics community, the existing theories from other fields such as solid mechanics, fracture mechanics, dynamic theories of other materials (metal, ceramics, polymer etc.) could be referred to. Third, the field tests during construction and operation of major engineering projects need to be conducted. This needs collaboration with the industry from civil engineering, mining engineering, hydraulic engineering, bridge engineering, petroleum engineering etc. Last but not least, the dynamic disaster mitigation and prevention technical measures for engineering projects during engineering

construction and operation periods will be set up. The applications of those technical measures to major engineering projects could facilitate minimizing the discrepancy between the theoretical prediction and actual performance, and mitigating and preventing dynamic disasters.

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