

# Using P wave modulus to estimate the mechanical parameters of rock mass

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**Abstract** Obtaining reasonable and reliable mechanical parameters of rock mass in engineering is a challenge. These parameters are difficult to obtain from a large sum of field tests due to the restrictions of time and costs. In this paper, linear equations of estimating rock mass mechanical parameters based on the P wave modulus are proposed through dimensional analysis. The field tests data of the Xiangjiaba, Baihetan, and Jinping I dam foundations are discussed to verify the universality and applicability of these linear equations. In addition, a new equation for calculating the disturbance factor  $D$  based on the P wave modulus is presented to estimate the mechanical parameters of rock mass in the disturbed zones, and then the field test data of the Three Gorges Project (TGP) shiplock slope are studied to verify the equation. The results show that the linear equations based on the P wave modulus have higher correlation than other function equations based on the P wave velocity. Therefore, the empirical equations using P wave modulus are feasible for estimating the mechanical parameters of rock mass.

**Keywords** P wave modulus · Deformation modulus · Cohesion · Disturbance factor  $D$

## Introduction

The mechanical parameters of rock mass are the premise and basis for the stability analysis of slope and underground engineering. These parameters are directly related to the safety and economy of engineering. Therefore, obtaining reasonable and reliable mechanical parameters is a major subject of rock mechanics and rock engineering.

A field test is the most direct method to obtain these parameters, but requires considerable costs and involves difficult operational processes (Li 2001; Gokceoglu et al. 2003; Hoek and Diederichs 2006; Kayabasi et al. 2003). To obtain the mechanical parameters of rock mass more conveniently, some empirical equations have been proposed by researchers to estimate these mechanical parameters (Palmström et al. 2001; Zhang and Einstein 2004). Some scholars estimated the field modulus and strength through the field P wave velocity on rock mass (Chang et al. 2006; Yasar and Erdogan 2004; Sharma and Singh 2008), and some scholars established relationships on rock specimens (Wang et al. 2015; Pan et al. 2013). The P wave is often used, as the test is relatively cheap, non-destructive, and easy to carry out (Khandelwal 2013). At the same time, the propagation of P waves is influenced by some measurable parameters, such as rock density, jointing, and the relative quality of joints (Mineo et al. 2015). P wave velocity measured on a rock mass can reflect various characteristics, which is different from that on a rock specimen. Fractures and joints in rock mass can decrease the P wave velocity. In addition, geo-stress in the rock mass can affect the compactness of the thin layer structure or fracture, making P wave propagation different from that on the unloading rock specimen. However, not all properties of rock mass can be reflected on P wave velocity. Gupta and Sharma (2012) pointed out there is no relation between the

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unconfined compressive strength and P wave velocity of quartzites. Regarding the relations between the deformation modulus and P wave velocity of rock mass, some scholars proposed their empirical equations. Barton (2002) and Wu et al. (1998) deduced these equations through two relations, one is between the Q system and deformation modulus and the other is between the Q system and P wave velocity, Zhou et al. (2005) fitted a power function equation from the Shuibuya project and Li and Zhou (2010) fitted an exponential equation using data of more than 20 projects. Song et al. (2011) proposed a power function equation using the data from the Maerdang project. These empirical equations between the P wave velocity and deformation modulus are shown in Table 1. Although the method using these empirical equations to estimate mechanical parameters are simple and cost-effective, these empirical equations have limitations, i.e., the disunity function equations are not convenient for engineering applications.

In this paper, we propose empirical equations that use the P wave modulus to estimate rock mass mechanical parameters such as deformation modulus and cohesion through theoretical analysis and statistical analysis. In addition, an empirical equation for calculating the disturbance factor *D* based on the P wave modulus is presented to estimate the mechanical parameters of the rock mass in disturbed zones. Then, some field data obtained from several Chinese projects are analysed to prove the feasibility of these empirical equations.

### Estimation of deformation modulus using P wave modulus

#### Empirical equations

The P wave modulus is defined as the ratio of axial stress to axial strain in a uniaxial strain state (Mavko et al. 1998). It is deduced from the theory of elastic wave propagation, which is based on elastic mechanics. The P wave modulus is shown in Eq. (1).

$$M = \rho V_p^2 \tag{1}$$

where *M* is the P wave modulus;  $\rho$  is the density; and  $V_p$  is the P wave velocity.

The P wave velocity in Eq. (1) is deduced from wave equations. The particles in the continuum medium under stress would deviate from the original balance position, and then the produced elastic stress would lead to the movement of the adjacent particles. Therefore, the elastic wave is generated in the medium. The particles are tiny compared with the elastic wave length. The wave equations are shown as follows:

$$\left. \begin{aligned} \rho \frac{\partial^2 u}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial x} + \mu \nabla^2 u + \rho X \\ \rho \frac{\partial^2 v}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial y} + \mu \nabla^2 v + \rho Y \\ \rho \frac{\partial^2 w}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial z} + \mu \nabla^2 w + \rho Z \end{aligned} \right\} \tag{2}$$

where *u*, *v* and *w* are the displacements of the *X*, *Y*, and *Z* directions respectively;  $\lambda$  and  $\mu$  are the Lamé constant,  $\theta$  is the bulk strain, and  $\nabla^2$  is the Laplacian.

The three equations in Eq. (2) are solved by partial differentiation on *x*, *y*, *z*, respectively, and then they are added as follows:

$$\frac{\partial^2 \theta}{\partial t^2} = [(\lambda + 2\mu)/\rho] \nabla^2 \theta \tag{3}$$

Thus, the P wave velocity is given as

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{4}$$

Then the P wave modulus is expressed as follows:

$$M = \rho V_p^2 = \lambda + 2\mu \tag{5}$$

Some empirical equations between the deformation modulus and P wave velocity of rock mass are discussed above (Barton 2002; Wu et al. 1998; Zhou et al. 2005; Li and Zhou 2010; Song et al. 2011) and show that P wave could reflect the deformation property of rock mass. The deformation modulus is related to the density, lithology, and jointing of rock mass. Therefore, the factors

**Table 1** Correlation function between  $V_p$  and  $E_0$

Author	Empirical equations	Source	Type of equation
Barton	$E_0 = 10 \times 10^{(V_p - 3.5)/3}$	Deduced	Exponential
Wu XC	$E_0 = (V_p - 3500)/80$	Deduced	Linear
Li WS	$E_0 = 0.708e^{0.00069V_p}$	Goupitan project	Exponential
Zhou HM	$E_0 = 0.004V_p^{5.133}$	Shuibuya project	Power
Song YH	$E_0 = 0.02386V_p^{4.3266}$	Maerdang project	Power

$V_p$  is P wave velocity,  $E_0$  is deformation modulus of rock mass

influencing the deformation modulus can be summarized as P wave velocity and density, which can be obtained simply on rock mass. The equation between the deformation modulus and influence factor is given as follows:

$$E_0 = f_1(V_p, \rho) \quad (6)$$

The dimension of each variable is  $[E_0] = ML^{-1}T^{-2}$ ,  $[V_p] = LT^{-1}$ ,  $[\rho] = ML^{-3}$ . According to the Pi theorem (Sonin 2004), the dimensionless function relation can be obtained as follows:

$$f_2\left(\frac{E_0}{\rho V_p^2}\right) = 1 \quad (7)$$

The deformation modulus is the internal quality of rock mass, and its dimension is equal to the P wave modulus. According to dimensional consistency, the linear empirical equation between the P wave modulus and deformation modulus is as follows

$$E_0 = a_1M + b_1, \quad (8)$$

where  $a_1$  and  $b_1$  are the correction coefficients related to the lithology, structural plane, and weathering degree. The linear equation can be fitted by limited measured data, and then the values of  $a_1$  and  $b_1$  are obtained.

For the density discussed above, some scholars have assumed that it is a constant value in their studies. Actually, there is a slight change in the density of rock mass under different conditions. There are some equations between the density and P wave velocity by scholars (Gardner et al. 2012; Zhu et al. 1995; Pappalardo 2014; Gaviglio 1989). For convenience, the density in the Eq. (1) is calculated though the empirical Eq. (9) given by Gardner.

$$\rho = 0.31V_p^{0.25} \quad (9)$$

where  $\rho$  is in units of  $g/cm^3$  and  $V_p$  is in units of m/s.

### Field data analysis

To verify the universality of the linear Eq. (8), 197 sets of the P wave modulus and deformation modulus of several rock types are collected at some Chinese dam sites, such as dacite in the Rumei project, sandstone in the Guanyinyan project, basalt in the Baihetan project, crystalline limestone in the Sanhekou project, and sandstone in the Xiangjiaba project. The deformation modulus and P wave velocity are all measured on the rock mass. P wave of these projects are all acoustic wave measured in boreholes. The parallel boreholes are arranged at the surrounding of loaded plates which are used to measure deformation modulus. Acoustic tests should be carried out before the deformation test, which reflect wave velocity of rock in the natural state. The

P wave was measured according to Chinese National Standard (2013), GB/T 50266-2013. The P wave modulus is calculated by Eq. (1).

The regression relation between the P wave modulus and deformation modulus is shown in Fig. 1 and Eq. (10). The regression coefficient  $R^2$  is 0.662.

$$E_0 = 0.30M - 1.114 \quad (10)$$

To examine the significance of the regression Eq. (10), an F test is used. Using a significance level of 5 %, the F value of the data is 381.92 and larger than the significance level, which means that Eq. (10) is able to provide an interpretation for the linear relation between the P wave modulus and deformation modulus with certain satisfactory performance. As a result, the universality of the linear Eq. (8) is verified.

Figures 2, 3, and 4 depict the regression equations of three rock types including volcanic rocks (basalt and dacite), sedimentary rocks (sandstone, limestone), and metamorphic rocks (metamorphic sandstone), respectively. The regression coefficient of equation on sedimentary rocks is higher than the other two equations. Lithology is a factor influencing the P wave propagation in rock mass, which is reflected in  $a_1$  and  $b_1$  of the empirical equation  $E_0 = a_1M + b_1$ .

To verify the applicability of the Eq. (8), two cases including the Xiangjiaba and Baihetan projects are discussed. The Xiangjiaba gravity dam (Zeng 2011) is the last stage power station on the Jinsha River at the border between Yunnan province and Sichuan province in which the dam height is 161 m, the length of dam crest is 897 m, the reservoir capacity is  $51.63 \times 10^8 m^3$  and the power generation is 6000 MW. The rock mass of the dam site is composed of sandstone and siltstone. Large-scale tests cannot be conducted on the river bed with thicker sand gravel cover (approximately 500 m in width). The sand gravel cover is about 10 m in thickness on river bed near the dam line and 20–30 m on the left side of the floodplain area. Therefore, the deformation tests and

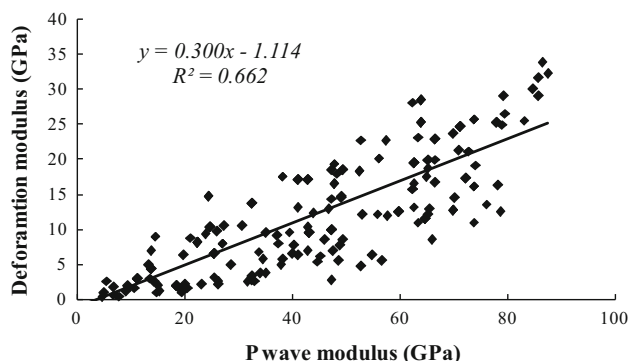
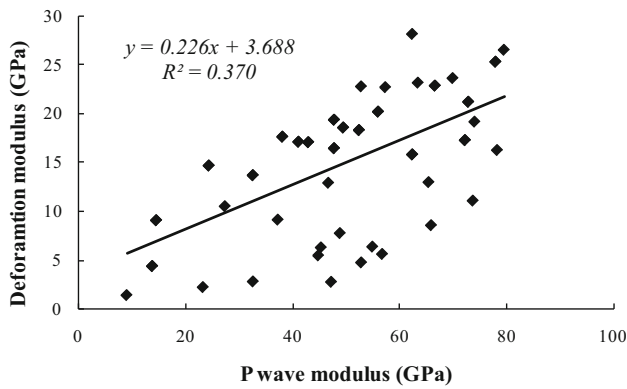
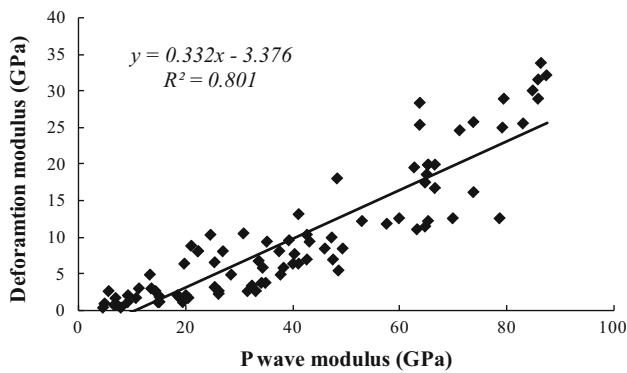


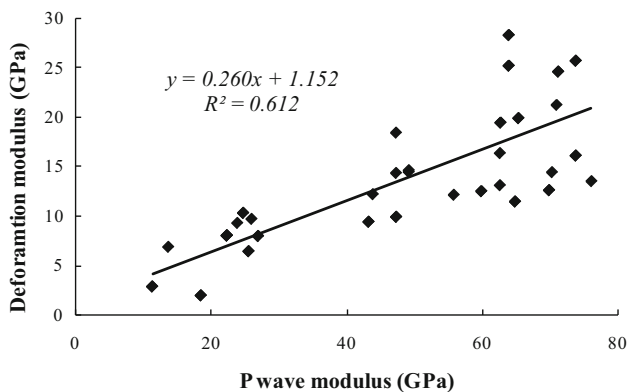
Fig. 1 Linear fitting curve between  $M$  and  $E_0$



**Fig. 2** Linear fitting curve of volcanic rock mass between  $M$  and  $E_0$



**Fig. 3** Linear fitting curve of sedimentary rock mass between  $M$  and  $E_0$



**Fig. 4** Linear fitting curve of metamorphic rock mass between  $M$  and  $E_0$

acoustic test for sandstone were taken in adits of the slope, which could well reflect the characteristics of the rock mass. Baihetan, a double-curvature arch dam currently under construction, is located downstream of the Jinsha River at the border between Ningnan County of Sichuan province and Qiaojia County of Yunnan province. The asymmetric V-shaped valley is characterized by the gentle slope at left bank and the steep slope at

right bank. Rock mass of the dam site is composed of Emeishan basalt of the upper Permian system and breccias lava. Notably, the columnar jointed basalt rock mass characterized by anisotropic structure was fully developed among the  $P_2\beta_3$  layers. In order to analyze different types of basalt, 28 sets of deformation modulus test taken in adit include 13 sets of the columnar jointed basalt, seven sets of amygdaloidal basalt, three sets of breccia, and five sets of aphanitic basalt (Zhou et al. 2015). The deformation modulus and the corresponding P wave velocity of the two projects are shown in Table 2. P wave modulus is calculated by the Eq. (1).

The linear regression relations between P wave modulus and deformation modulus are shown in Fig. 5. Three regression relations, the linear relations, power function relations, and exponential function relations, between the P wave velocity and deformation modulus are shown in Figs. 6, 7, and 8, respectively. The regression equations and the respective regression coefficients are summarized in Table 3. The regression coefficients of the linear regression equations between the P wave modulus and deformation modulus reach 0.774 and 0.977, which reveal that the correlations of the equations are higher than the relations between the P wave velocity and deformation modulus. The result shows that the linear equation has a certain applicability for estimating the deformation modulus of rock mass.

## Estimation of cohesion using P wave modulus

### Empirical equations

An important mechanical parameter of rock mass, i.e., cohesion, is often obtained using an in situ shear test and empirical equation method. The empirical equation method is based on limited number of measured cohesion and related geological parameters like GSI, BQ. BQ is the rock mass basic quality index described in the Chinese Standard of Engineering Classification of Rock Masses (GB50218-94).

Song and Ju (2012) proposed Eq. (11) between cohesion and the BQ value through information from the Maerdang project. Based on the statistical analysis of more than 200 sets of measured data, a regression equation between BQ and RMR was given by Wu and Liu (2012), which is shown in Eq. (12).

$$c = 5 \times 10^{-6} \text{BQ}^{2.0339} \quad (11)$$

$$\text{BQ} = 80.786 + 6.0943\text{RMR} \quad (12)$$

The relation between cohesion and RMR is given as follows:

**Table 2** Field tests data ( $V_p$  and  $E_0$ ) of two projects

Xiangjiaba project			Baihetan project		
P wave velocity (m/s)	Deformation modulus (GPa)	Position	P wave velocity (m/s)	Deformation modulus (GPa)	Position
4563	12.19	96 m in PD44	4000	9.2	198 m in PD111
3700	2.69	45 m in PD44	5100	20.8	194.8 m in PD111
2110	2.03	28 m in PD44	4170	10.8	190.1 m in PD111
4420	8.56	134 m in PD28	5900	30.7	176.6 m in PD111
3730	6.85	84 m in PD28	5530	26.4	154.7 m in PD111
2891	1.71	47 m in PD28	5300	21.6	146 m in PD111
5050	16.69	185 m in PD34	5800	29.8	121.5 m in PD111
3333	2.61	165 m in PD47	5340	22.6	119 m in PD111
4070	13.18	114 m in PD47	4800	18.2	53.9 m in PD111
4733	11.90	25 m in PD35	4400	15.7	47.8 m in PD111
4000	9.62	64 m in PD37	2260	1.4	23.8 m in PD111
2467	4.96	0.9 m in J1	2070	1.3	7.4 m in PD111
1667	2.69	1.0 m in J2	3360	6.8	30.7 m in PD111
2950	6.38	0.5 m in J3	2700	2.6	6.6 m in PD716
1538	0.39	0.7 m in J4	3540	5	11.9 m in PD716
1588	0.93	1 m in S3	3100	2.9	26.3 m in PD716
1881	0.72	1.5 m in S4	4200	10.3	35.1 m in PD716
3032	8.87	2 m in S5	3160	3.8	39.65 m in PD716
			3530	5	55 m in PD716
			2500	1.5	79.1 m in PD716
			4820	17.1	101.6 m in PD716
			4720	16.3	104.3 m in PD716
			5100	22.2	107.5 m in PD716
			3110	5	11 m in PD923
			3670	11.6	28.5 m in PD923
			4150	11.2	34 m in PD923
			4800	16.5	117 m in PD113
			5300	21.7	118.3 m in PD112

PD is adit. J and S are boreholes

$$c = 5 \times 10^{-6}(80.786 + 6.0943\text{RMR})^{2.0339} \quad (13)$$

From Barton (2002), some relations between the RMR value and P wave velocity exist. Thus, there must be some relations between cohesion and the P wave velocity. Taking the linear equation between the P wave modulus and deformation modulus as a reference, a linear equation between the P wave modulus and cohesion is as follows:

$$c = a_2M + b_2, \quad (14)$$

where  $a_2$  and  $b_2$  are the correction coefficients related to the lithology, structural plane, and weathering degree.

### Field data analysis

To verify the applicability of the Eq. (14), two cases, the Jinping I and Xiangjiaba projects, are discussed. The

Jinping I arch dam (Fu 2009) is located at a sharp V-shaped valley of the Yalong River in Yanyuan County, Sichuan province. The rock mass of this dam site is composed of marble, sandy slate, metamorphic sandstone, greenschist, and lamprophyre. Marble is mainly at the right bank and at the part below EL 1820 m of the left bank. Sandy slate is at the left bank above EL 1820 m. The large scale direct shear test results of marble in adit and the corresponding acoustic velocity of the feasibility study stage are listed in Table 4. For the Xiangjiaba project (Zeng 2011), the cohesion measured by the large scale direct shear test and the acoustic velocity by the field test of sandstone with different weathering degree are shown in Table 4.

The linear regression relations between the P wave modulus and cohesion are shown in Fig. 9. Three regression relations, the linear relations, power function relations,

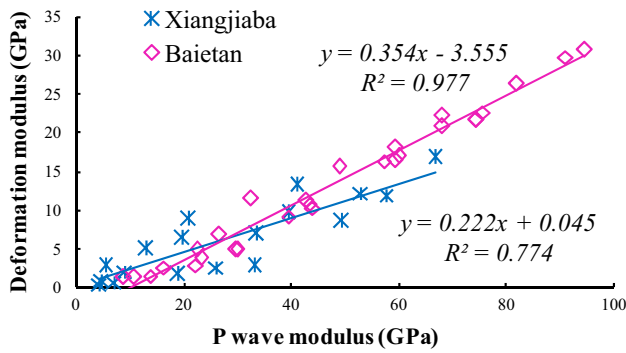


Fig. 5 Linear fitting curve between  $M$  and  $E_0$

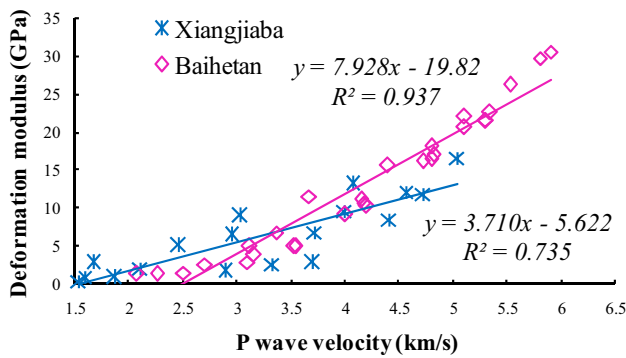


Fig. 6 Linear fitting curve between  $V_p$  and  $E_0$

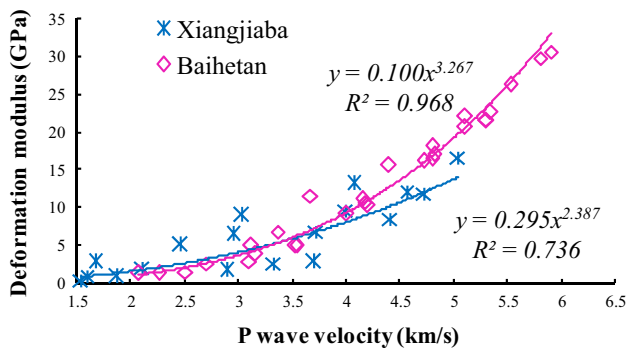


Fig. 7 Power function fitting curve between  $V_p$  and  $E_0$

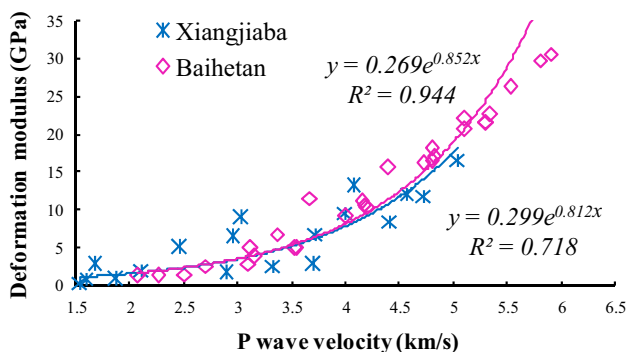


Fig. 8 Exponential function fitting curve between  $V_p$  and  $E_0$

and exponential function relations, between the P wave velocity and cohesion are shown in Figs. 10, 11, and 12, respectively. These regression equations and the respective regression coefficients are shown in Table 5. The regression coefficients of the linear regression equations between the P wave modulus and cohesion reach 0.878 and 0.936, revealing that the correlations of the equations are higher than the correlations of the equations between the P wave velocity and cohesion. The result shows that Eq. (14) has a certain universality and applicability for estimating the cohesion of rock mass.

### Estimation of disturbance factor $D$ using P wave modulus

#### Empirical equations

In the 2002 edition of the Hoek–Brown failure criterion (Hoek and Carranza-Torres 2002), the disturbance factor  $D$  depends on the disturbance degree of the rock mass subjected to blast damage and stress relaxation. The range of  $D$  values is between 0 and 1.  $D = 0$  indicates the excellent quality of the rock mass, and  $D = 1$  indicates significantly poor quality.

There is no consistent method currently available to determine the disturbed factor  $D$ . Some scholars have proposed that the loss of elastic modulus should be used to present the disturbance degree of rock mass. Through comparison of the elastic modulus of excellent rock mass and disturbed rock mass, the disturbance factor  $D_1$  estimated by using the P wave velocity was proposed by Yan and Xu (2005) as follows:

$$V = \sqrt{\frac{E(1 - \mu)}{\rho(1 + \mu)(1 - 2\mu)}} \quad (15)$$

$$D_1 = 1 - \frac{V_p^2}{V_0^2} \quad (16)$$

where  $V_0$  is the P wave velocity of the excellent rock mass treated with  $D = 0$  and  $V_p$  is the P wave velocity of the disturbed rock mass.

The deformation modulus of rock mass was given by Evert Hoek and Carranza-Torres (2002) as follows:

$$E_0 = \left(1 - \frac{D}{2}\right) \sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{\frac{GSI-10}{40}} \quad (\sigma_{ci} < 100\text{MPa}) \quad (17)$$

$$E_0 = \left(1 - \frac{D}{2}\right) 10^{\frac{GSI-10}{40}} \quad (\sigma_{ci} > 100\text{MPa}) \quad (18)$$

Sun and Lu (2008) compared the deformation modulus of excellent rock mass and the disturbed rock mass as shown in Eq. (19).

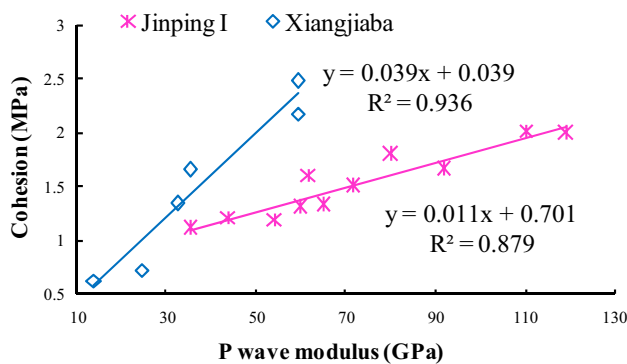
**Table 3** Deformation modulus regression equations and  $R^2$

Project	Regression equation	Regression coefficient, $R^2$	Project	Regression equation	Regression coefficient, $R^2$
Xiangjiaba	$E = 0.222M + 0.045$	0.774	Baihetan	$E = 0.354M - 3.555$	0.977
	$E = 3.710V_p - 5.622$	0.735		$E = 7.928V_p - 19.82$	0.937
	$E = 0.295V_p^{2.387}$	0.736		$E = 0.100V_p^{3.267}$	0.968
	$E = 0.299e^{0.812V_p}$	0.718		$E = 0.269e^{0.852V_p}$	0.944

**Table 4** Field tests data ( $V_p$  and  $c$ ) of two projects

Xiangjiaba project			Jinping I project		
P wave velocity (m/s)	Cohesion (MPa)	Position	P wave velocity (m/s)	Cohesion (MPa)	Position
4790	2.18	32 m in PD17	3799	1.11	–
4790	2.48	38 m in PD17	4188	1.22	–
3660	1.35	313 m in PD17	4615	1.20	–
3800	1.66	45 m in PD34	4810	1.31	–
3226	0.73	Surface	4888	1.61	–
2500	0.63	Surface	4991	1.33	–
			5212	1.50	–
			5484	1.80	–
			5821	1.66	–
			6314	2.02	–
			6547	2.00	–

PD is adit



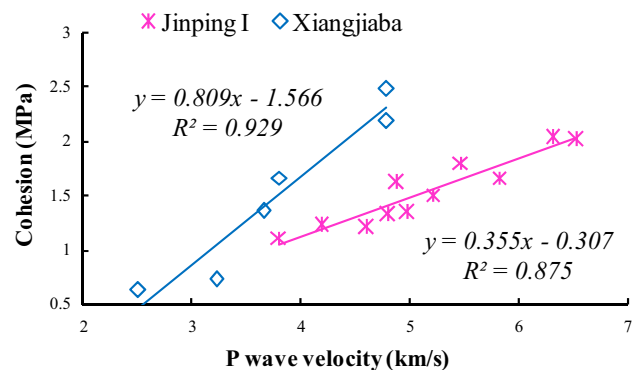
**Fig. 9** Linear fitting curve between  $M$  and  $c$

$$\frac{E_{UD}}{E_D} = \frac{1}{1 - D_2/2} \tag{19}$$

The disturbance factor  $D_2$  is given as follows:

$$D_2 = 2 \left( 1 - \frac{E_D}{E_{UD}} \right) \tag{20}$$

$$D_2 = 2 \left( 1 - \frac{V_e^2}{V_0^2} \right) \tag{21}$$



**Fig. 10** Linear fitting curve between  $V_p$  and  $c$

where  $E_{UD}$  is the deformation modulus of excellent rock mass.  $E_D$  is the deformation modulus of the rock mass with certain disturbed degree.

The density and Poisson's ratio in Eq. (16) and Eq. (21) are assumed as constant values. However, there is a large difference between the two expressions of disturbance factor  $D$ . In Eq. (16),  $D$  is calculated by comparing the elastic modulus through the wave equation directly. In Eq. (21),  $D$  is calculated by comparing the deformation modulus.

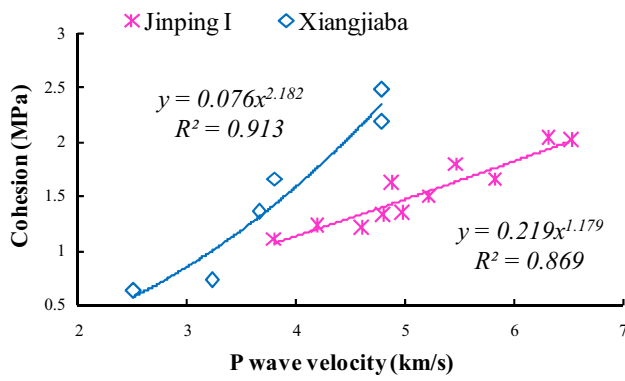


Fig. 11 Power function fitting curve between  $V_p$  and  $c$

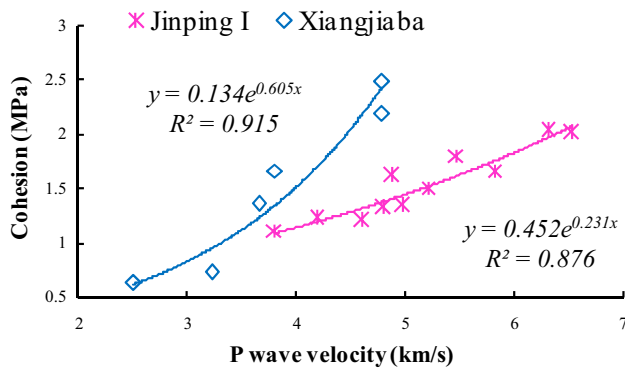


Fig. 12 Exponential function fitting curve between  $V_p$  and  $c$

The two equations of disturbance factors  $D$  discussed above are lower for the large disturbance conditions. Therefore, we consider the influence of density and then give the relation as Eq. (22) between disturbance factor  $D$  and P wave modulus according to the Eq. (1) and Eq. (21).

$$D = 2 \left( 1 - \frac{M_D}{M_{UD}} \right) \tag{22}$$

where  $M_D = \rho_p V_p^2$  and  $M_{UD} = \rho_0 V_0^2$ . The density is calculated by Eq. (9).

**Field data analysis**

The permanent shiplock is an important part of the Three Gorges Project (TGP), which is located on the left bank of the mountain. The TGP permanent shiplock slope is 120 m

in high and 1.6 km in length. The main rock type is granite ( $\sigma_{ci} \geq 125\text{MPa}$ ). Because of stress release in rock mass caused by deep excavation, the stability of the slope is extremely complex. Acoustic wave tests were taken in adits of slope after the excavation completed. According to the test results, the slow P wave velocity in the area about 20 m from the slope surface shows that the excavation disturbed zone exists.

The P wave velocity of rock mass at the area with a long distance from the free surface is 5.6 km/s (Zhong and Chen 2013). We consider that the disturbance factor  $D$  of the rock mass is 0 because of the good quality of the rock mass with minimal disturbance. The deformation modulus and cohesion of rock mass under three conditions, i.e., strong disturbed degree, medium disturbed degree and minimal disturbed degree, are shown in Table 6, where the disturbance factor  $D$  is calculated by Eqs. (16), (21), and (22), respectively. The deformation modulus is calculated by Eq. (18). The results of the calculations are shown in Table 6.

For the rock mass with minor disturbed degree, the deformation modulus calculated through the three equations show little difference. For the rock mass with strong disturbed degree, the deformation modulus obtained through Eq. (22) is closer to the field test results. Therefore, Eq. (22) is more reasonable for estimating the disturbance factor  $D$  with P wave modulus for the rock mass with strong disturbance.

**Conclusions**

The following conclusions can be drawn from the present study:

1. The linear equations between the P wave modulus and mechanical parameters of rock mass were established according to the dimensional consistency. Through 197 sets of field tests results, the universality of the linear equation was verified. In addition, the linear regression equations showed satisfactory best fit to the data from the Xiangjiaba, Baihetan, and Jinping I projects as the corresponding regression coefficient  $R^2$  values were larger than  $R^2$  of the equations between the P wave velocity and mechanical parameters, which demonstrated the

Table 5 Cohesion regression equations and  $R^2$

Project	Regression equation	Regression coefficient, $R^2$	Project	Regression equation	Regression coefficient, $R^2$
Jinping I	$c = 0.011M + 0.701$	0.879	Xiangjiaba	$c = 0.039M + 0.039$	0.936
	$c = 0.354V_p - 0.304$	0.875		$c = 0.809V_p - 1.566$	0.929
	$c = 0.220V_p^{1.176}$	0.869		$c = 0.076V_p^{2.182}$	0.913
	$c = 0.453e^{0.231V_p}$	0.876		$c = 0.134e^{0.605V_p}$	0.915



**Table 6** Estimated deformation modulus of rock mass through three equations respectively

Disturbed degree	Distance from the free surface (m)	P wave velocity (km/s)	Measured deformation modulus (GPa)	Calculated deformation modulus (GPa)		
				Obtain through Eq. (16)	Obtain through Eq. (21)	Obtain through Eq. (22)
Strong	5	2.7	9.2	29.9	11.3	9.4
Medium	20	5.1	39.7	44.4	40.2	39.3
Minor	45	5.4	47.8	46.8	45.1	44.7

applicability of the linear equations. Therefore, the linear equations based on the P wave modulus exhibited certain universality and applicability for the estimation of the deformation modulus and cohesion of rock mass.

2. We proposed an equation that estimated the disturbance factor  $D$  based on the P wave modulus and obtained the mechanical parameters of rock mass in disturbed zones. The estimated deformation modulus was close to the measured data at the excavation disturbed zone of the TGP permanent shiplock slope, especially in the zone with strong disturbed degree. The results showed that the equation was feasible for estimating the disturbance factor  $D$ .

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