Investigation of Failure Mechanism and Process on Excavation Damaged Zone/Disturbed zone (EDZ) of Underground engineering in Rock

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Abstract

In the design and construction of underground engineering (tunnels, caverns, shafts, hydro-electric stations...), investigation the mechanical behavior of underground excavations, that include the influence of the rock mass characteristics on the Excavation Damaged Zone (EDZ), is necessary. More ever, the presence of the excavation damaged zone (EDZ) around an excavation boundary can significantly affect the overall performance of the excavation and the general safety of people and equipment. Hence, it has been an important subject of research on various rock mass excavation projects. For Houziyan Hydropower station in Sichuan Province of P.R.China, the understanding of the EDZ is essential for optimal design and construction of rock support. In this paper, the investigation of the main objective EDZ was conducted at the Hydropower station using geophysical test methods (acoustic waves and digital borehole camera techniques). The results of the experiments indicated that tensile failure was the microscopic failure mechanism of rock in the excavation damaged zone. The damage of caverns surounding rock masses was usually resulted from the redistribution of stress undisturbed rock mass in caverns excavation process. The results are consistent with our predictions of forming progression and failure mechanism of rock on construction.

Keywords: Houziyan Hydropower station; Excavation damaged zone; Failure process; Acoustic waves; Digital borehole camera.

1. Introduction

In recent years, more and more vast and large-scale Hydropower stations have been designed and constructed in China. These constructions all involved in large-scale excavations, which provoked a zone, excavation disturbed or damaged zone (EDZ) beyond the excavation boundary, where the rock was disturbed or damaged and its physical, mechanical properties were greatly changed (Malmgren, Saiang, Töyrä, & Bodare, 2007). EDZ is the zone around an excavation where in situ rock mass properties and conditions have been altered due to stress redistribution, fracturing, blasting damage have taken place (Martino & Chandler, 2004), (S. Wang, Lee, Ranjith, & Tang, 2009). In general, a redistribution of stresses and rearrangement of rock structures will occur in this zone and result in drastic changes of stress distribution, mainly through the fractures and cracks induced by excavation. Therefore the investigation of the EDZ around an underground excavation is especially important for underground construction and supports that require a long term stability, and it is always one of the major research topics for the underground research facilities and stability for many countries including China (Sheng, Yue, Lee, Tham, & Zhou, 2002), (Zou & Xiao, 2010), (Feng, Rutqvist, & Pan, 2013). There are some researches that have studied the EDZ around ungderground opening, for example: using a micromechanics model based on the images of the distribution given by the digital borehole camera (Li et al., 2011); using Acoustic wave method for assessment EDZ (Xu et al., 2014), (Kwon, Lee, Cho, Jeon, & Cho, 2009). Another researcher adopted the acoustic emission and microseismic events (Cai & Kaiser, 2005); for instance quantification of the damage degree and accumulative opening displacement of cracks (Wu, Liu, Liu, Zhuang, & Yan, 2009); the realistic modeling and fracture process (S. Wang et al., 2009).

In this paper, application of geophysical methods investigate the EDZ provided images of the distribution given by digital borehole camera and acoustic waves velocity changes through the formation of the EDZ. We will get a visual knownledge of the cracks, deformation and microfractures of surrounding rock mass. Then the width, depth and fracture process of the EDZ will be analysized for applying during construction and support process of the Houziyan Hydropower station project.

2. Background

2.1. Houziyan Hydropower station

The Houziyan Hydropower station is located on the Dadu river in Sichuan province, China. It is one of the deepest Hydropower stations underground rock engineering in China. The Houziyan Hydropower station installed gross capacity of 1700MW with three caverns that dimensions (width x high x length)m: Main powerhouse (29.2x68.7x219.5)m; Main Transformer chamber (18.8x25.2x139)m; Tailrace surge chamber (23.5x70.0x140.5)m. The stations are being excavationed for Dolomitic limestone, Metamorphic limestone rock with the maximum overburden of 660m below. There are some of large faults and folds have been distributed along them.

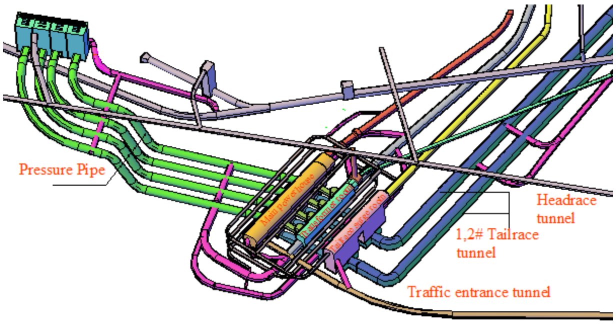
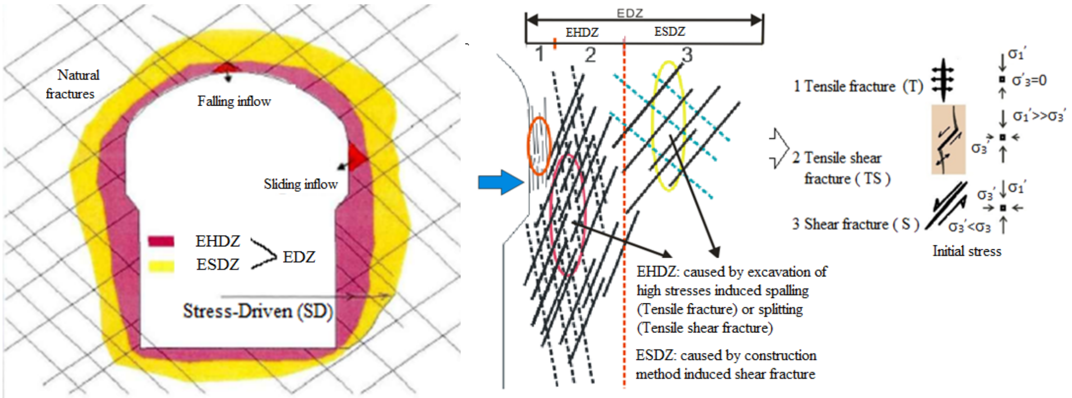


Fig. 1. Sketch of underground caverns diversion system of Houziyan Hydropower station

2.2 . The excavation damaged zone (EDZ)

So far, the EDZ around underground opening has been investigating and different definitions and understanding have obtained (Davies & Bernier, 2003). There are multiple terms that have the same meaning with the terminology in excavation of damage, for example: rock loosening ring, loose circle, disturbed zone, plastic zone, damaged zone, etc. (Cai & Kaiser, 2005), (Martino & Chandler, 2004), but in fact, the EDZ terms is adopted to describe the deformation and failure processes of an EDZ, including the surrounding rock mass of crack initiation, extensions and unstableness (Tsang & Bernier, 2004), (S. Wang et al., 2009), (Siren, Kantia, & Rinne, 2015). In this paper, the term EDZ will be used as a contraction Excavation Damage Zone and the difinition of EDZ is defined as: EDZ is the zone around an excavation at where in situ stress conditions the properties of the rock mechanical have been changed due to stress redistribution induced fracturing, blasting damage have taken place. It can be devided into two sub-zones excavation highly damaged zone (EHDZ) and slightly damaged zone (ESDZ) as shown in Fig. 2a. The EHDZ contains a lot of cracks of macro-scale fracturing which are caused either by excavation or high stresses induced spalling, splitting, etc. (EHDZ is also referred as excavation fracture zone). The ESDZ defined as a zone containing newborn cracks that is caused by stresses redistribution induced fracture (shear fracture) as shown in Fig. 2b.



(a) (b)

Fig. 2 Overview of the different damage zone and Stress-Driven mechanical failure modes

2.3 The excavation damaged zone of failure process

When underground engineering are opening, the underground engineering surrounding rock will typically exhibit a variety of failure modes where the rock failure and processes controlled by geology properties and conditions. According to the stress condition and experimental methods on Houziyan Hydropower station, surrounding rock mass failure processes is the result of tensile crack initiation, propagation, accumulation, and interaction which were subdivided into two major groups: Gravity-Driven control of structure (G), Stress-Driven (SD)

(1). Failure process by Gravity-Driven (G)

Under the condition of high situ-stress, the failure of rock is often controlled by persistence natural fractures or joints. As the geostress magnitude increases, natural fractures becomes clamped and failure of rock is then increasingly dominated by new stress-induced fractures, frequently growing parallel with the boundary of underground openings. No matter how many faces it has, the rock can move initially in only a few ways: by falling, by sliding on one face, or by sliding on two faces (or by combined sliding and rotation), as show Fig. 3. The stress-induced fractures are primarily parallel to the maximum principal stress around the openings.

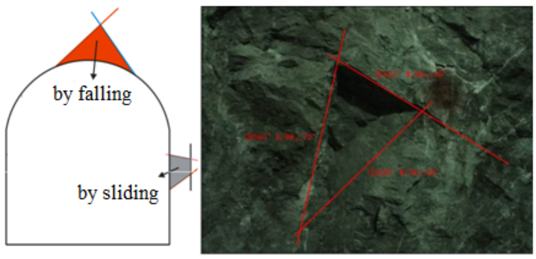


Fig. 3 Schematic of Failure process by Gravity-Driven control

(2). Failure process by Stress-Driven (SD)

In order to excavate an underground space under high geostress, the original properties of a rock or rock mass near an underground engineering are changed after an excavation due to a stress redistribution. Hence, produced new cracks that is easily initiation greaten in surrounding rock, subsequently the newborn cracks propagate and perforate into the new cracks. Consequently, they caused rock damage not only by sliding or falling but also by the main failure modes: unravelling, spalling, splitting, rockburts, shear failure, etc. The main failure modes are grouped as: Tensile fracture (T), Tensile shear fracture (TS) and Shear fracture (S) as shown in Fig. 2b.

According to the result of test data at field have demonstrated that the dominant failure mechanism in Dolomitic limestone, metamorphic limestone rock near underground excavation in Houziyan Hydropower station is tensile in nature, such tensile stress can be generated in an overall confined surrounding rock mass.

3. Methods for assessing the EDZ

3.1 Digital borehole camera method

The Digital Borehole Camera system is based on direct optical observations in boreholes, see for example (C. Wang, Ge, & Bai, 2001), (Wei, Qin, Tang, & Wang, 2007), (Malmgren et al., 2007). The system digitally records the 360° continuous projection of the borehole wall. Measurements of strike and dip of bedding and joint planes, along with other geologic analysis, are possible in both air and clear fluid filled holes with this system. The supplier of this system is RaaX Co. Ltd (www.raax.co.jp) and the test arrangement is shown in Fig. 4.

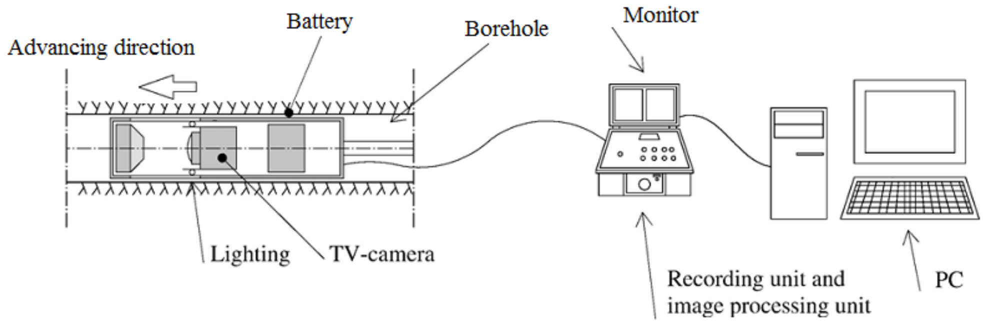


Fig. 4 Configuration for the Digital borehole camera system

From this system, the EDZ of width and mechanical properties can be interpretability determine, such as fractures, the structural plane and cracks by TV image. According to results of borehole images during different excavation periods can identify other orientations of old and new cracks, predicted newborn cracks location, the problem of depth and density of each segment, moreover the variables in order to determine the damage zone boundary.

3.2 Acoustic waves method

The basis for acoustic waves method is that, all of density and fracture in the rock mass will be reflected by variation in the acoustic waves of velocities and depth. Based on the acoustic waves of velocity versus the depth in borehole can be qualitatively determined by characteristic position of depth and width of the EDZ .

For the convenience in the actual operation, the following transformation can be done to the acoustic waves of velocitiy of characteristic, the acoustic waves of velocity can be expressed as

$$E = \rho V_p^2 \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon}, \tag{1}$$

$$\overline{E} = \rho \overline{V}_p^2 \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon}, \tag{2}$$

Where E is Young' modulus of the undamaged zone, $\overline{E}$ is Young' modulus of the damaged zone V_p, is P wave velocity of the undamaged zone, $\overline{V}_p$, is P wave velocity of the damaged zone, ρ is rock density and υ is in Poisson's ratio.

The excavation of an underground opening will alter the mechanical behaviour of defect, extend and exchange that includes the cracks and fracture. We can use the damage factor D (Xu et al., 2014) for quantitative determination EHDZ or ESDZ by P wave velocity (Malmgren et al., 2007).

$$D = 1 - \frac{\overline{E}}{E} = 1 - \frac{\rho \overline{V}_P^2}{\rho V_P^2} = 1 - \frac{\overline{V}_P^2}{V_P^2}. \tag{3}$$

Table. 1 Damage factor D and EDZ classifi catior in Houziyan Hydropower station

EDZ classify	Damage factor D	Vp velocity m/s	EDZ of characeristic
EHDZ	>0.65	<3500	On the curves of acoustic velocity, the P wave

			velocity is suddenly mutate and significant attenuate compared to the initial. The newborn cracks have been changed and significantly opened.
ESDZ	0.2 - 0.65	3500 - 5500	The P wave velocity is a concussion with low rate in cracks location. The velocity mutate from low to high in a long time on the curves of acoustic velocity. The newborn cracks can be formed but not really significant.
Undamage	<0.2	> 5500	The P wave velocity may be smooth or may be a little fluctuation on the curves of acoustic velocity.

4. Results

The experiment in Main powerhouse at 1711 level can be divided into three zones named HyzM-1, HyzM-2, HyzM-3 to determine the EDZ by the digital borehole camera and acoustic wave test. The digital borehole camera was used first then the acoustic wave test was used later. The configuration of the test area is shown in Fig. 5 (red lines).

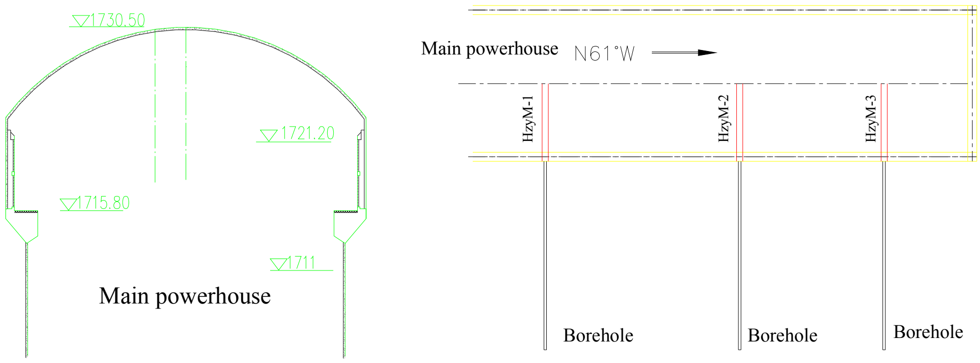
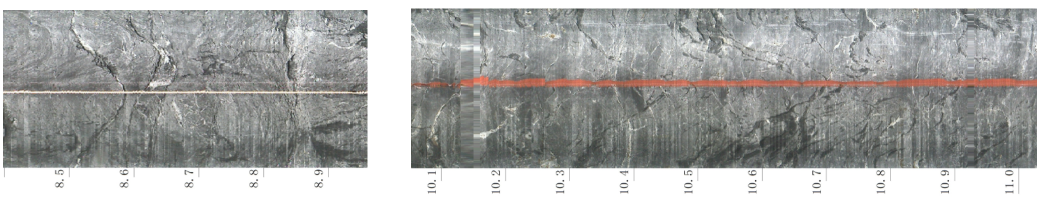


Fig. 5 Configuration of experimental in Main powerhouse

4.1 Depth and Width of EDZ in HyzM-1 experimental zone

The investigation of the main objective EDZ characteristics was conducted at the HzyM-1 by using the digital borehole camera, the results were used to infer the damage zone boundary. Then the deformation of main powerhouse surrouding rock mass was determined based on the damage zone boundary. According to the results of the digital borehole camera, the major deformation of surrouding rock mass cracked at the segment of 0 – 11.4m depth of the borehole are shown in Fig. 6



(a) (b)

Fig. 6 Distribution of cracks recorded by digital borehole camera in HyzM-1

The surrounding rock mass was highly damaged at the segment of 0 - 8.9 m depth of the borehole. Thus, this segment can be regarded as the ultimate boundary for the EHDZ, or in other words, the width of the EHDZ is 8.9 m (Fig. 6a). The segment from 8.9 to 11.4 m depth of borehole is slightly damaged. Hence, this segment belongs to the ESDZ as shown in Fig. 6b.

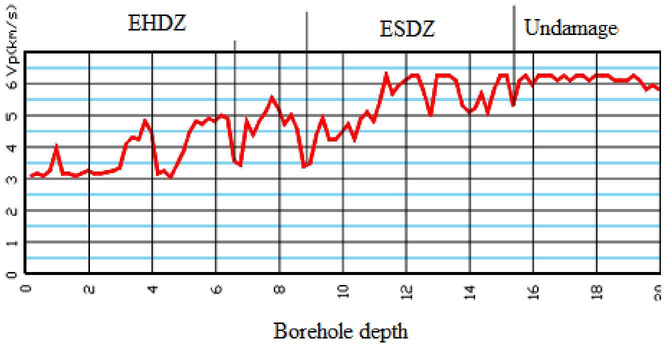
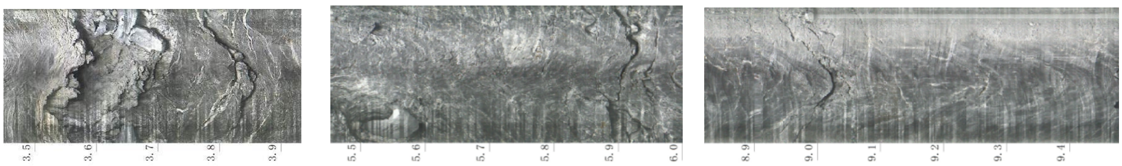


Fig. 7. Results of acoustic wave phase velocity versus borehole depth in HyzM-1

According to the result of curves of acoustic velocity versus the depth, there is an increase of the acoustic velocity correlated to borehole depths. The results of the acoustic velocity measurement indicate a depth of the damage zone in the surrounding rock mass at the range of 0 - 15.5m. If the average acoustic velocity is lower than 3.5 km/s or between 3.5 km/s and 5.5 km/s or higher than 5.5 km/s, then the damage zone boundary is considered as EHDZ or ESDZ or basically undamaged zone, respectively (Tab.1). Thus, the position of the ultimate boundary of the EHDZ and ESDZ are 9.0 m and 15.5 m in depth; and the width of EHDZ and ESDZ are 9.0 m and 6.5 m (15.5-9.0=6.5 m), respectively (Fig. 7).

4.2 Depth and Width of EDZ in HzyM-2 experimental zone

According to the analysis of images recorded in borehole HyzM-2, the surrounding rock mass was highly damaged at 3.9 m in depth (Fig. 9a); hence, the width of the EHDZ is 3.9 m and this position can be regarded as the ultimate boundary for the EHDZ. The segment from 3.9 - 9.0 m depth of the borehole is slightly damaged (Fig. 9b); hence, the width of the ESDZ is 5.1 m (9.0 - 3.9=5.1 m) Therefore, at the 9.0 m in depth can be regarded as the ultimate boundary for the ESDZ and the segment from 9.0 m depth of the borehole onwards is basically undamaged.



(a) (b) (c)

Fig. 9 The position of each crack at which can be considered the boundary of EDZ

As one can see, the deformation of surrounding rock mass obtained by the results of curves of acoustic velocity versus the depth is shown in Fig. 10, the main damaged in the surrounding rock mass is most distribute at the range of 0 - 8.7 m depth.

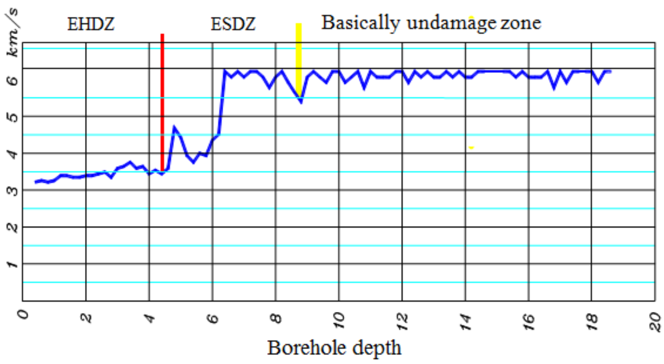
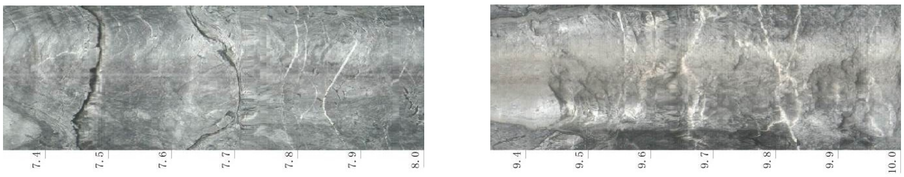


Fig. 10. Results of acoustic wave phase velocity versus borehole depth in HyzM-2

The ultimate boundary for the EDZ are determined based on the average acoustic velocity. That is, if the average acoustic velocity is lower than 3.5 km/s or between 3.5 km/s and 5.5 km/s or higher than 5.5 km/s, then the damage zone boundary is considered as EHDZ or ESDZ or basically undamaged zone, respectively (Tab.1). That mean, at the position of 4.3 m and 8.7 m from the borehole's mouth are the ultimate boundary of the EHDZ and ESDZ, respectively (Fig. 10). Based on the analysis above, the width of the EHDZ is at 4.3 m and the width of the ESDZ is at 4.4 m (8.7 - 4.3=4.4m) and the segment from 8.7 m depth of borehole onwards is basiclly undamaged.

4.3 Depth and Width of EDZ in HzyM-3 experimental zone

According to the displacement of surrounding rock mass in Fig. 11, it can be found that the obvious deformation occrurs at the 7.7 m depth of borehole, the surrounding rock mass was slightly damaged. Therefore, this position can be regarded as the ultimate boundary for the EHDZ, that means the width of the EHDZ is 7.7 m (Fig. 11a). From the results in the above part, we conclude that the ESDZ segment is from 7.7 m away access borehole.



(a) (b)

Fig. 11. Photos of the segmen of the ESDZ by digital borehole camera in HyzM-3

According to the result of curves of acoustic velocity versus the depth, there is an increase of the acoustic velocity correlated to borehole depths. The results of the acoustic velocity measurement indicate a depth of the damage zone in the surrounding rock mass at the range of 0 - 14.4m. Based on the EDZ of characeristic (Tab. 1), we get the damage zone boundary is considered as EHDZ and ESDZ are 8.3 m and 15.2 m depth; and the width of EHDZ and ESDZ are 8.3 m and 5.8 m (14.2-8.3=5.9 m), respectively, and the segment from 14.2 m depth of borehole onwards is basiclly undamaged (Fig. 12).

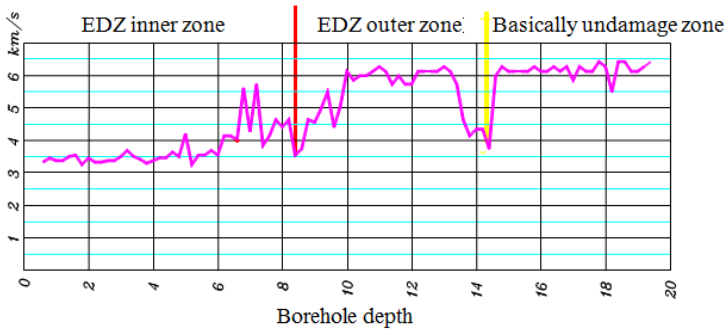


Fig. 12 Results of acoustic wave velocity versus borehole depth in HyzM-3

5. Discussion

The digital borehole camera can give us images of the cracking or fracturing induced in the surrounding rock mass, while testing methods of acoustic wave can not. As the previous describe, the results of digital borehole camera methods can be effectively used to identify the surrounding rock mass deformation process including the surrounding rock mass of crack initiation, extension and unstablenes. According to the result from the analysis of images recorded in borehole, it not only provided photographic images of the surrounding rock mass beyond the EDZ boundary, but also provided important predictions for the fracture intensity and cracks distribution. We would like to know whether the distribution of structures or cracks recorded by digital borehole camera can be used to determine the EDZ boundary included EHDZ, ESDZ and basiclly undamaged zone. Li et al (2011) demonstrated that it is possible to predict the EHDZ of depth and width (Li et al., 2011) but can not predict ESDZ by the distribution of structures or cracks recorded by digital borehole camera. Therefore, combination of the digital borehole camera method with other methods is necessary.

The results of acoustic wave testing methods were very useful to understand the results from borehole camera measurements. The results of the acoustic wave measurements confirmed the distribution of cracks. The significant influence of cracks was analysed, and the correlation between fracture density and acoustic measurements was obvious as shown in Tab. 2.

Tab. 2. Results of EDZ depth from borehole camera and acoustic wave measurements

Test zone	Borehole camera method		Acoustic wave method	
	EHDZ (m)	ESDZ (m)	EHDZ (m)	ESDZ (m)
1	8.9	> 2.5	9.0	6.5
2	3.9	5.1	4.3	4.4
3	7.7	>2.3	8.3	6.6

Based on the results from Tab. 2, the digital borehole camera is the main method to investigate and determine the EHDZ but it is impossible to determine exactly the depth and width of the ESDZ, as such case we must use the acoustic wave methods to determine the ESDZ. Therefore, the results of acoustic wave testing methods were very useful to determine exactly the depth and width of the ESDZ.

6 . Conclusions

In Hydropower station, determination exactly the depth and width of the EDZ is very important for the safety of people and equipment while constructions, especially operations in a long term. The understanding of the EDZ is essential for optimal design and construction of rock support. In this paper, the the digital borehole camera and acoustic wave methods are used to determined failure process of surrounding rock mass and EDZ. Based on the results of geophysical test methods conducted at the Hydropower station, some conclusions can be drawn from the present investigation as follows:

1. From the results of digital borehole camera, we can determine exactly rock deformation such as fractures and cracks during different periods of excavation, newborn cracks location, depth and density of problem segments, moreover more information can be given in order to determine the EDZ inner zone boundary.
2. The results of acoustic wave testing methods were very useful to determine exactly the depth and width of the EDZ, especially to determined the EDZ outer zone.
3. Until now, the Houziyan Hydropower station EDZ has been continuously changing, therefore, the results collected from these measurements are very important for the investigations of forming progression and failure mechanism of rock mass to support construction, especially for stable operation in a long term.

Acknowledgment

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