Study on the deformation characteristics and dynamic mechanism of seismic fractures in Wenchuan earthquake shattered slopes

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Abstract

Numerous shattered slopes triggered by wenchuan earthquake, the shattering area were large and the seismic fractures were wide distribution, mostly threatened the post-hazard reconstruction. According to the characteristics of seismic fractures in shattered slopes, the research results show: (1)The seismic fractures was divided into six types: surface type, transfixing type, strike type, tendency type, closure type, extension type from through survey the morphological characteristics and deformation indications; (2)On the whole the Seismic fractures was N30º～60ºE trending, which accords with the whole strike of active fault in wenchuan earthquake; (3)mainly distributed in seismogenic faults area or ridge、and steep with slow border area; (4)well extension, high open degree, upper wide and lower narrow of profile morphology, fillings less or no, mainly mixed stone fragments, with aerial phenomena. Based on the theory of fracture mechanics, the mechanism of seismic fractures was belong to tensile crack, the deformation and failure process of structural planes under dynamic action was divided into rupture, expansion and arrestability three stages.

Keywords: wenchuan earthquake, shattered rockmass, seismic fracture, geohazards

1. Introduction

Tens of thousands of collapse, landslides and secondary geological disasters triggered by Wenchuan Earthquake. Earthquake induced a large number of slope geological disasters, also caused a potential disaster—Slope shattered deformable body which namely shattered rockmass. The shattered rockmass as a geological phenomenon, it was mainly affected by the earthquake force under the certain geological conditions (Liang et al. 2003; Feng et al. 2009; Liang et al. 2009). The dynamic effect of seismic wave in rockmass destroyed the rockmass structure, its whole structure varied (Shao 2005; Zuo et al. 2008). The most typical feature of slope shatter-destroyed is that the seismic fractures developed

The deformation, instability of shattered rockmass has controlled by seismic fractures, it is a potential disaster. The shattered rockmass has no macro destruction features such as large deformation, large displacement as other destruction forms, it was an inherent rockmass damage, also it was the main cause of secondary disasters after the earthquake taken place frequently. Study these seismic fractures has important significance to recognize the deformation and failure, formation mechanisms of shattered rockmass correctly.

2. Seismic fracture classifications and failure characteristics

The rockmass structure were cracked open by earthquake force, so the seismic fracture formed. The classification of seismic fracture should corresponds to its formation mechanisms, now the classification research to fractures mainly based on the visual, intuitive shape of survey(Xie 1988). The classification analysis to fractures mainly based on its distribution, development characteristics, deformation features, and make it possible to predict its deformation and destruction. Based on this consideration, the seismic fractures was divided into six types: surface type, transfixing type, strike type, tendency type, closure typ, extension type from the morphological characteristics and deformation features.

2.1 Surface type seismic fracture features and failure characteristics

Surface type seismic fracture was refer to the rockmass surface shattered longer length from its characteristics, but its width and visible depth is generally small. Small scale of such fractures were developed in all kinds of slope structure, and there is no obvious directional distribution, it distributed in the rockmass surface, and had poor deep interconnectivity (Fig 1).

(I) (II)

Fig. 1 Surface seismic fracture

In accordance with the extension characteristics of surface type seismic fracture can be divided into broken line type, Linear type. From its combination features can be divided into en-echelon type, crossover type.

[1] broken line type: The spreading direction in plane of seismic fractures was turning、bent point of the polyline or arc-shaped, and then continue to extend(Fig. 1 I).

[2] Linear type: The overall spreading direction in plane of seismic fractures was extended straight, little change in direction, no significant turning or bending in the process of extending(Fig. 1 II).

[3] En-echelon type: it formed by a series of seismic fractures whose direction substantially the same, en-echelon distribution presented on the plane, seismic fractures were broken line or linear type(Fig 2).

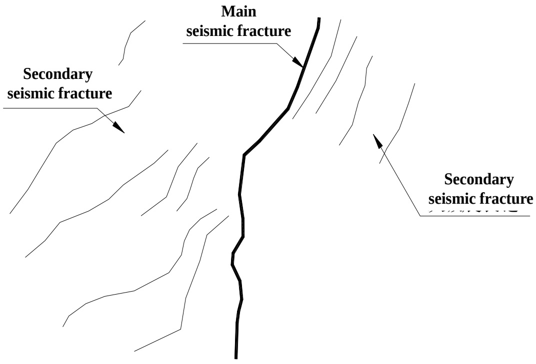

Fig. 2 Distribution schematic diagram of en-echelon type seismic fracture

[4] crossover type: it formed by the two or three groups of seismic fractures whose extension direction were different, cross each other, the distribution shape on the plane was "X" or "Y"shaped(Fig 3).

(I) “X” shaped seismic fracture (II) “Y” shaped seismic fracture

Fig. 3 Crossover type seismic fracture

Surface seismic fracture were exist in the rockmass surface, they can't control the deformation、instability of rockmass. However, this type of seismic fractures distributed generally, higher density developed in local position, thereby it destroyed the overall structure of rock mass. And it easy to become a good way to rainwater infiltration when experience rainfall conditions.

2.2 Transfixing type seismic fracture features and failure characteristics

Comparatively speaking to seismic fracture surface, the transfixing seismic fracture not only long extending length, but also large opening degree, visible depth was up to 10m. The fracture had good interconnectivity, linear extension in plane, joint interface jagged, throughout inside the rockmass by the form of pinch-out. For survey, the majority of seismic fractures belong to this type(Fig. 4).

Fig. 4 Seismic fracture throughout inside rockmass

The development scale of ransfixing seismic fractures were large and had good interconnectivity, it caused significant damage to rockmass structure and affect the deformation and instability of rockmass. Through the investigation of fractures on slope, such fractures developed in better position as slope top, steep slow border, free face to formed the trailing edge or side edge boundary of cutting rock mass, it become the main controlling factors of shattered rockmass stability. Seismic fractures cutting rockmass to formed the dangerous rock body on slope(Fig. 5).

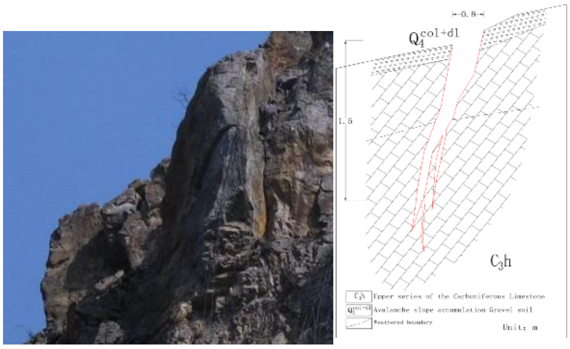

Fig. 5 Dangerous rock formed by seismic fracture cutting

Seismic fractures was filling less or no. They could further extended when encountered the rainfall or vibrate interference. When the fractures continued to run through the locked segment in shattered rockmass, the locked segment could suddenly snipped once the tensile stress of rockmass was greater than the tensile strengt under the action of gravity, earthquake force even wind. Then dangerous rock separated from the maternal rock to drop and formed rolling rock. Through the collapses investigation, the perforate seismic fractures became the main controlling factor of collapse disasters after earthquake. Such seismic fractures were developed in a large scal、strong interconnectivity, they often caused great collapse hazard.

2.3 Strike type seismic fracture features and failure characteristics

According to the extension direction of seismic fractures, the strike type seismic fracture was refer to its length along the strike direction was larger than along the dip direction, fracture developed mainly along its strike. The extension direction of strike type seismic fracture was identical or similar to the direction of tectonic force (such as the strike of fault). These seismic fractures extended along its strike, they had strong directional (Fig 6). Since this type of seismic fractures developed was mainly due to the effect of tectonic force, so their developmental scale were generally larger.

Fig. 6 Seismic fracture developed near the fault

Strike type seismic fractures exposed on slope by lesser extent of subjected to the influence of terrain and surface features, their extension length along the strike direction was large. Seismic fractures were mainly distributed in the vicinity of fault. It was due to the strong earthquake force existed at the fault, higher degree of rockmass shattered, fractures could easily developed along the strike direction of fault. And seismic fractures which existed at other locations, owning to their extend process was limited by the influence of terrain and surface features, so the characteristics along the strike extension was not obvious. The strike of this type seismic fracture was N30°～60°E by field investigation, seismic fractures which developed along their strike direction were located in the vicinity of fault.

The length along strike of strike type seismic fracture was longer, it could constituted the instability range boundary of shattered rockmass and controlled a wide range of rockmass unstable. The rockmass structure around this type of seismic fractures was poor, higher degree of shatter-damaged. Once the shattered rockmass produced deformation and instability, major destructive formed.

2.4 Tendency type seismic fracture features and failure characteristics

The tendency type seismic fracture was refer to its extension direction mainly along its dip direction. For the developmental morphology, the length along dip direction was greater than along its strike direction, its development was extended into the deep of rockmass. This type of seismic fractures developed in various locations on slope, especially developed at ridge、steep with slow border area.

Most seismic fractures belonged to this tendency type through investigated on slope. Although its length exposed on ground was short, owning to it was extended into the deep along its dip direction, its visible depth was up to 10m in the deep of rockmass. There are certain distribution characteristics in such seismic fractures, the Ladder type、 “Y” -shape type and Trace-back type had presented in the morphology of profile combination (Fig. 7). Ladder type seismic fractures was characterized by a series of fractures which inclined、extended to the same direction, parallel or nearly parallel to each other. Due to the visible depth limited in such seismic fractures, so this type fractures may also intersected in the deeper position of rockmass. The characteristics of “Y” -shape type seismic fractures was that a series of different tendencies seismic fractures crossed in the extend process to the deep, “Y” -shape presented in the profile. Trace-back type seismic fracture was refer to the fractures occurred one or more branches, the secondary seismic fractures which continuous or intermittent appeared in its extend process into the deep.

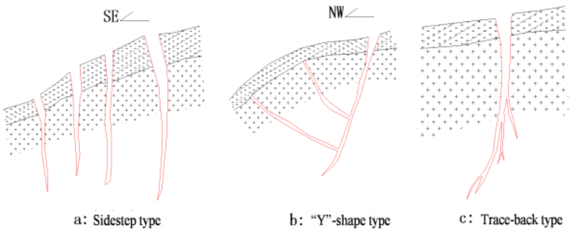

Fig. 7 Combination schematic diagram of tendency type seismic fractures

Tendency type seismic fractures cutting rockmass, constituted the instability boundaries of shattered rockmass, formed dangerous rock hanged on the slope. Owning to the length of seismic fracture extending to deep, good continuity with aerial phenomenon, it often become a good channel for rainwater、groundwater infiltration, could easily cause the instability of shattered rock mass to collapse. This type of seismic fractures was wide distribution on slope, so the formation of damage is relatively large.

2.5 Closure type seismic fracture features and failure characteristics

For the extending trendence in the distribution plane of seismic fractures, the joint interface on this type of fractures uneven in extension process, at both ends of the fracture closed or nearly closed, but the intermediate portion is open, small opening width (Fig. 8).

Fig .8 Closure type seismic fracture

Closure type seismic fractures were mainly distributed in the better parts of rockmass structure. The better the overall structure of rockmass, the less damage extent by seismic forces to the rockmass structure. Seismic fractures occurred by rockmass tension crack in the extending process was restricted, it discontinuous distributed by the form of beaded-shape in slope surface. This fracture was small degree opening, the joint interface on both sides in rockmass gradually filling at later under the action of gravity、fracture deposits.

Since this type of seismic fractures intermittent distributed, poor continuity, small degree opening, the joint interface gradually healing later, devastating limited, but it discontinuous distributed in the slope surface, with a certain degree of ductility, it destroied the overall structure of slope. Seismic fracture filling less or no, overhead rockmass, it could constitute a good channel for rainwater、groundwater infiltration. Once it connect with other fractures which was large opening、good continuity、strong interconnectivity, these fractures could cause cracking scaling, accelerating the rockmass deformation instability, so destructive.

2.6 Extended type seismic fracture features and failure characteristics

Extended type seismic fracture refers to its extension in the section, one end was gradually open, and extended to the slope surface with opening gradually large, one end gradually pinch out into the deep, and had the wedge-shaped gap of wide upper-narrow lower. This kinds of fractures was large opening degree, filling less or no, the joint interface was rough and jagged(Fig.9).

Fig. 9 Extended type seismic fracture

Through slope seismic fractures investigation, the fracture which was wide upper-narrow lower shaped in section, large degree opening, overhead rockmass. It mostly belong to the extension seismic fracture. This seismic fracture formated by the high degree of shatter damaged caused by seismic forces to the rockmass structure, severely damaged, the development of fractures extended along the direction of seismic force. Using the theory of fracture mechanics, fractures begin to expand when its tip stress intensity factor is greater than rockmass intensity factor by seismic force, this can be roughly divided into three stages: initial shattered stage, fracture formed, development stage, fracture propagation、extending to surface stage(Lin et al. 1986).

Extended type seismic fractures were widely developed on the slopes according to the survey, especially developed at crest、ridge or steep with slow border area, a certain size distributed. This seismic fractures not only destroied the rockmass structure, but also large degree opening, overhead rockmass. After the earthquake, frequent aftershocks、rainfall and wind forces were constantly changed the state of shattered rockmass balance, these made the seismic fractures continues to expand、extend. These fractures lead the rockmass instability and collapse.

3. Seismic fracture development characteristics

Investigated the basic characteristics of seismic fractures, their spread、development characteristics、deformation signs had some corresponding characteristics.

3.1 Spatial distribution characteristics

Seismic fractures was N30 ^{o} ～ 60 ^{o} E trending(Fig.10), it is basically the same with the triggering seismic faults in Wenchuan earthquake, the extension direction of fractures has obviously effected by the triggering seismic fault. Some larger degree of shattered opening fractures spread by linear shaped, good extension, generally not subjected to the influence of the terrain and surface features in its extending direction. Some seismic fractures were corresponding with the fault which influenced their development. American scholars (Leonard 1929; Holzer et al. 1987)put forwarded the view of tectonic origin in seismic fractures by analysis the earthquake force, they thinked the tectonic is the dominant factor in formation and development of seismic fractures.

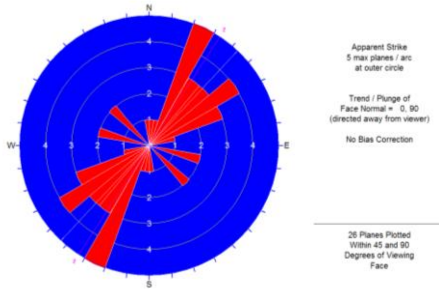

Fig. 10 Statistical graph of typical seismic fractures

The distribution of seismic fractures were mainly due to the effect of triggering seismic faults, they were mainly distributed in the vicinity of causative fault or ridges position and steep slow border in slope, these positions were also the site of strong seismic force.

3.2 Extended length characteristics

The extension length of seismic fracture refers to its continuous length exposed on the slope surface. The fractures extended length generally longer, more than 6m. Some shattered serious fractures was up to 10m in length, portion extended to the top of slope. Collapse pit、tensional slot were exposed in the process of extending(Fig.11). Large number of secondary seismic fractures were distributed around the main seismic fractures. The secondary seismic fractures discontinuous distributed and poor continuity.

Fig. 11 Tensile groove developed

3.3 Opening degree characteristics

The opening degree of seismic fracture mainly refers to the width of crack in rock and soil mass by shocked tension in the earthquake force. Through the survey, the opening degree of seismic fracture was the form of wide upper-narrow lower shaped, pinch out into the deep(Fig.12). Cai and Zhang (2001) indicated that the seen seismic fracture was wedge shaped fractures on the wide upper-narrow lower form. For some better overall structure of rockmass, the opening degree was small, generally only a few centimeters to a dozen centimeters; Some rockmass with poor structure and structural plane significantly developed, their fractures opened a greater degree. And the seismic fractures located around the triggering seismic faults had the wedge-shaped gap of wide upper-narrow lower, the opening degree in top was closed to 1m, it is illustrated the rockmass around the faults was serious shattered.

Fig. 12 Schematic section of seismic fracture

The shattered width of Surveied fractures were 20cm or more, inclination angle greater than 60 °, extended to deep by jagged-shaped, but it extending to the deep, the shattered width became smaller gradually.

3.4 Filling characteristics

These seismic fractures were large opening degree generally, filling less or no, overhead rockmass. The joint interface was relatively new and bedrock exposed, straight or jagged, extending longer. Wide upper-narrow lower shaped in the form of fractures, shattered stone fragments were filled in it. Both sides of rock and soil collapsed was caused by some seismic fractures which had large degree opening(Fig.13).

Fig. 13 Collapse induced by the slope rockmass were shattered

4. Seismic fracture mechanics mechanism analysis

Seismic fracture was mainly caused by the earthquake force. Refraction and reflection of seismic waves occurred in the structural plane when the seismic waves affected it (Fig.14), so the rockmass in structural plane shattered crack due to the tension crack which caused by the accumulated stress(Zhang et al. 1993). The slope damage caused by seismic force was closely related to the effect of seismic waves, seismic wave is divided into P-wave (longitudinal wave) and S-wave (shear wave), both joint action at the structural plane of rockmass. P-wave and S-wave with frequency up-down and horizontal vibration, this generated n-pull、anti-pull repeated stress to rockmass in the structural plane, and rockmass in the structural plane cracked open along the structure plane under the dynamic action of powerful earthquake force(Zhang et al. 2005; Feng et al. 2009; Newmark 1965). The shear strength of structure plane quickly lower owning to it suffered repeated shear stress, rockmass was cutted along the structure plane by the action of strong shear stress, rockmass opened and deformed. Myer (1990) studied the propagation characteristics of seismic waves through the rockmass joint surface and the force between the rockmass interface controlled by the Coulomb criterion. Liang (2003) holded that the structure plane formed shattered face by the earthquake force, the rockmass above the surface would out of the parent rock and continue to movement, and the rockmass below the surface would generate a new free surface due to the influence of upper shattered face.

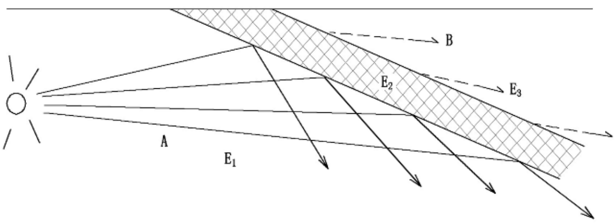

Fig. 14 Schematic diagram of stress wave propagation effected by the structural plane

Seismic fracture formed by the process of rupture、perforation、extend in rockmass, internal fracture was further developed into large fracture in the slope at last. The ruptured of rockmass was mainly due to seismic waves, Fig 15 shows a simplified seismic waves schedule figure, Fig 16 is a figure of simplified equivalent stress intensity factor curves. Use the fracture mechanics theory to analysis the process of rupture、propagation and crack arrest in rockmass (Li 2010).

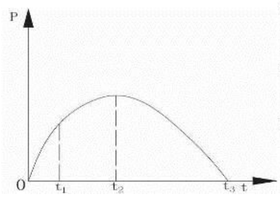

Fig. 15 Curve diagram of seismic wave course

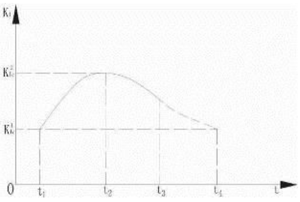

Fig. 16 Curve diagram stress intensity factor

4.1 Fracture criterion

Combined with fracture mechanics, the rupture criterion of rockmass is the maximum stress intensity factor criterion, law of K, the rockmass will produce tensile failure if the stress intensity is greater than the fracture toughness. At time t=0, seismic waves is not yet in effect, the structure plane only in the static stress field, $K_I < K_{Ic}^1$ (K_{Ic}^1fracture toughness), it is in the closed state. With the seismic waves apply to the structure plane, the earthquake intensity gradually apply to the structure surface. Increase over time, the intensity gradually increase, the equivalent stress intensity factor will also increase accordingly, the stress intensity factor reaches K_{Ic}^1 with the increase of earthquake intensity until $t=t_1$ the rockmass will rupture along the structural plane if it met the fracture conditions.

4.2 Extension process

The fracture generated in the internal of rockmass after it rupture. With the continuing effect of seismic waves ($t_1<t<t_2$), the fracture continue to expand, this is driven by the equivalent stress intensity factor KI, the maximum rate of expansion obtained by the fracture when the seismic waves reach the peak intensity at $t=t_2$, K_I reach maximum K_{Ic}^2. The stress intensity factor KI is gradually reduce with the weakening of seismic intensity after $t>t_2$, the effect course of seismic waves will end until $t=t_3$. The effect of seismic waves will stop after $t>t_3$, extended fracture is in the static stress field. If the stress intensity factor is still greater than the fracture toughness of rock mass, the fracture will continue to extend in the static stress field, it stop the extension until $t=t_4$.

4.3 Crack arrest evidence

As the seismic intensity decreases, the energy reduce, the fracture stop rupture when the stress intensity factor is less than the fracture toughness. For the structural plane effected by strong earthquake force, it may have higher stress intensity factor after the earthquake stop. The fracture in the static stress field may continue to extend、until the crack arrest conditions is met.

5. Conclusions

In summary, through detailed investigation and analysis to the deformation characteristics、deformation and failure mechanisms、deformation kinematic characteristics of slope seismic fracture, the results show that:

Based on the morphological characteristics and deformation deformation features of slope seismic fracture, the seismic fractures was divided into six types: surface type、transfixing type、strike type、tendency type、closure type、extension type. Surface seismic fracture in accordance with its extension characteristics could be divided into broken line type、Linear type. From its combination features can be divided into en-echelon type、crossover type.

Slope seismic fractures was N30º～60ºE trending, they were mainly distributed in the vicinity of causative fault or ridges position and steep slow border in slope. Seismic fracture was well extension、high open degree、obvious connectivity and large scale. Upper wide-lower narrow of profile morphology, pinch out into the deep, fillings less or no.

Based on the rock fracture mechanics mechanism, combined with the stress intensity factor to analysis the shatter damage mechanism of the structure plane. The mechanics type of slope fractures mainly belong to the tension crack, rock structure plane would rupture to generate crack under the dynamic action, crack gradually extend to become the penetrating tensional seismic fracture.

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