Dynamic response of the Daguangbao landslide triggered by the Wenchuan earthquake with a composite hypocenter

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ABSTRACT

To identify the correspondence between the different dynamic responses of the Daguangbao landslide and the different faulting mechanisms of the composite-hypocenter, the whole hypocenter of the Wenchuan earthquake was divided into four sub-hypocenters. On another hand, based on the location of the Daguangbao landslide, the composite-hypocenter was divided into the Initial Sub-hypocenter, the Approaching Sub-hypocenter, the Local Sub-hypocenter, the Receding sub-hypocenter and the Terminal sub-hypocenter. Subsequently, dynamic response of the landslide was modeled by using UDEC software. The results show that progressive damage and critical failure of the mega landslide are triggered by the second sub-hypocenter. Simultaneously, with respect to the second classification basis, its progressive damage is induced by the Approaching Hypocenter and the Local Hypocenter in time sequence. The Local Hypocenter triggers its critical failure. During the long-runout stage, besides the local topography, its self-gravity poses a dominant contribution to the dynamic responses of the landslide. Especially, the inertial seismic force is another key factor that triggers the ejection stage of the landslide. The following seismic forces triggered by the corresponding sub-hypocenter influence the long-runout stage slightly. The horizontal seismic force poses a dominant contribution to the progressive damage and critical failure of the mega landslide.

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1. Introduction

As one of consequences of the endogenous processes of the Earth, a strong earthquake always creates disparities in the earth’s microtopography. For example, obvious relative movements on each side of a seismogenic fault. On the other hand,
earthquake-triggered landslides eliminate the inequalities to some extent by destroying mountains and filling valleys. Generated from a hypocenter, seismic waves transmit through the surface layers and cause great ground shaking continuously, which induces progressive dynamic damages in nearby slopes simultaneously (Singh et al. 2010; Parker et al. 2011; Gischig et al. 2015, 2016; Wolter et al. 2016). Finally, many coseismic landslides form simultaneously or later on (Tanyas et al. 2018, 2019). A long-runout sliding is an obvious characteristic of this type of landslide. Furthermore, after the progressive dynamic damage and critical failure of a slope, the micro topography rather than the seismic forces controls mainly the long run-out sliding.

The strong Wenchuan earthquake triggered about 15000 landslides, which caused great damage and brought many new related researches (Wasowski et al. 2011; Chen et al. 2014; Li et al. 2014; Zhang et al. 2014; Kritikos et al. 2015; He et al. 2017; Marc et al. 2017; Tanyas et al. 2017, 2018, 2019; Del Gaudio et al. 2011; Fan et al. 2018; Li et al. 2018; Yang et al. 2018; Domenech et al. 2019; Fan et al. 2019; He and Singh 2019; Zhang et al. 2011). The contents focused mainly on the temporal-spatial distribution, progressive damage and long-runout sliding, controlling factors and formation mechanisms of the coseismic landslides (Sato and Harp 2009; Yin et al. 2009; Chigira et al. 2010; Michele et al. 2010; Gorum et al. 2011; Qi et al. 2011; Xu et al. 2011; Yin et al. 2011; Luo et al. 2012; Sun et al. 2012; Huang et al. 2013; Huang and Fan 2013; Xu et al. 2013; Wang et al. 2014, 2015; Song et al. 2016). Especially, lots of studies on progressive damage mechanism, including spatial effect of the seismogenic fault, mechanical effect of the ground shaking, etc, of the landslides were conducted (Dai et al. 2011; Huang et al. 2012; Cui et al. 2018a; 2018b). The results are of great value for precaution and damage mitigation of the potential landslides in the future.

In fact, during the strong Wenchuan earthquake occurring, slopes near the surface ruptures of the Longmen Mountain fracture underwent continuous ground shaking when the fracture developed from the initial break located near the Yingxiu Town, Wenchuan County to the terminal break located at the Donghekou village, Qingchuan County. The fracture with an about 300-km length behaved obvious property of a composite hypocenter (Meng and Shi 2011) and belt-shaped spatial distribution (Li et al. 2008). The 240-km-long Yingxiu-Beichuan fault of the Longmen Mountain fracture, on which the earthquake nucleated, is characterized by two distinct faulting mechanisms, southwest and northeast of Beichuan town, respectively. In the southwest, the fault is prevalently reverse faulting. Contrarily, northeast of the town the fault plane is almost vertical and its two sides moved past each other almost exclusively horizontally, in a so-called strike-slip motion (Zhang et al. 2008; Huang and Fan 2013). With respect to the aforementioned fact, researches emphasizing the hypocenter with a composite property and a belt-shaped spatial distribution should be conducted further when response mechanisms of the coseismic landslides are identified. For example, was it the reverse faulting or the oblique-slip faulting that caused the progressive damages of the typical coseismic landslides triggered by the Wenchuan earthquake? It is a very interesting research to be conducted. However, few related results appear up to now (Cui et al. 2018a).
2. The details of the composite hypocenter

2.1. Hypocenter classification according to the seismogenic mechanisms

As mentioned above, seismogenic mechanism of the strong Wenchuan earthquake exhibits an obvious property of a composite hypocenter. The composite is embodied by the fact that the whole Longmen Mountain fracture consists of the dip-slip fault, the oblique-slip fault and the strike-slip fault from its southwest to northeast part. As far as a certain coseismic landslide is concerned, that which one triggered its progressive damage and critical failure is a very interesting question. Furthermore, spatial distribution of the composite hypocenter is an obvious belt-shape rather than a dot-shape (Cornell 1968; Kiureghian and Ang 1977; Shen et al. 1990; Chen et al. 2008). However, few researchers emphasized the composite property of the hypocenter, especially its influence to a certain landslide, when its detailed formation mechanism was identified.

In fact, a more detailed research result on the composite of the Longmen Mountain fracture that triggered the strong Wenchuan earthquake appeared soon after the earthquake occurred (Zhang et al. 2009). In detail, as shown in Figure 1a, the whole seismogenic fault consists of four sub-faults. The first one is the reverse fault situated from the southwest of the Yingxiu town to Wenchuan County with length of approximate 40 km, i.e., the line segment marked A in Figure 1. After its fractured, 7% of the total seismic moment was released. The second one is the oblique-slip fault situated from Wenchuan County to Maoxian County with length of approximate 90 km, i.e., the line segment marked B in Figure 1. The dip-slip, i.e., the reverse component of this oblique-slip fault is much larger than its strike-slip component. After its fractured, 61% of the total seismic moment was released. The third one is the oblique-slip fault situated from Beichuan County to Pingwu County with length of approximate 70 km, i.e., the line segment marked C in Figure 1. The dip-
slip, i.e., the reverse component of this oblique-slip fault is nearly equal to its strike-slip component. After its fractured, 9% of the total seismic moment was released. Finally, the fourth one is the strike-slip fault situated from Pingwu County to Qingchuan County with length of approximate 110 km, i.e., the line segment marked D in Figure 1. After its fractured, 23% of the total seismic moment was released.

With respect to the above fact on the composite hypocenter, the progressive damage and long-runout response of the Daguangbao landslide triggered by the strong Wenchuan earthquake was modeled by using UDEC software. The sub faults that triggered the progressive damage and critical failure of the landslide were identified. This modeling based on the composite hypocenter contributes a new insight into dynamic formation mechanism of the mega Daguangbao landslide.

### 2.2. Hypocenter classification according to the spatial location of the landslide to be modeled

Based on the spatial location of the Daguangbao landslide to be modeled, i.e., the icon DaGB in Figure 1 and the point D in Figure 2, as well as the realistic surface
damage after the Wenchuan earthquake, the composite of the hypocenter can be divided further from another respect. According to relevant regulations on engineering-site level and potential hypocenter in Evaluation of Seismic Safety for Engineering Sites (grant no. GB17741-2005) and Technical Code of Regional Tectonic Stability Investigation for Hydropower and Water Resources Project (grant no. DL/T5335-2006) issued in China, i.e., the scope of both lateral side, with each length of about 10 km, along an active fault is defined as a potential hypocenter, with respect to the hypocenter depth, i.e., about 15 km of the Wenchuan earthquake, the composite hypocenter in Figure 2 is divided into the Initial Hypocenter from the point a to the point b, the Approaching Hypocenter from the point b to the point c, the Local Hypocenter from the point c to the point d, the Receding Hypocenter from the point d to the point e and the Terminal Hypocenter from the point e to the point f.

The above terms are explained as follows. ①The Initial Hypocenter, which is located from the southwest to the northeast of Yingxiu town, develops northeastward approximate 30 km along the seismogenic fault. Its projection on line segment a-f is the segment a-b. Yingxiu town projects itself perpendicularly in the middle of the line segment a-b with a 30-km length, which is twice longer than the depth of the initial break of the composite hypocenter. ②The Local Hypocenter, which is located from the southwest to the northeast of the Daguagnbao landslide, develops northeastward approximate 30 km along the seismogenic fault. Its projection on line segment a-f is the segment c-d. The Daguagnbao landslide projects itself perpendicularly in the middle of the line segment c-d with a 30-km length, which is twice longer than the depth of the initial break of the composite hypocenter. ③The Terminal Hypocenter, which is located from the southwest to the northeast of the Donghekou landslide, develops northeastward approximate 30 km along the seismogenic fault. Its projection on line segment a-f is the segment e-f. The Donghekou landslide projects itself perpendicularly in the middle of the line segment e-f with a 30-km length, which is twice longer than the depth of the initial break of the composite hypocenter. ④The Approaching Hypocenter, which is located from the northeast of Yingxiu town to the southwest of the Daguagnbao landslide, develops northeastward approximate 60 km along the seismogenic fault. Its projection on line segment a-f is the segment b-c. ⑤The Receding Hypocenter, which is located from the northeast of the Daguagnbao landslide to the southwest of the Donghekou landslide, develops northeastward approximate 165 km along the seismogenic fault. Its perpendicular projection on line segment a-f is the segment d-e.

It is very important to note that there appeared strong surface damage along the surface rupture, which is shown in Figures 1 and 2, during the strong Wenchuan earthquake, for example, Yingxiu town, Beichuan county and Donghekou village. Therefore, according to the above hypothesis on the composite hypocenter and the results of the numerical modeling, the sub-hypocenter that triggered the progressive damage and critical failure of the Daguagnbao landslide was identified from another respect. This modeling contributes another new insight on dynamic formation mechanism of the mega landslide.
3. The numerical modeling on the dynamic response of the mega landslide

3.1. The geological and geomorphological setting and model

The Wenchuan earthquake triggered thousands of landslides, which caused tens of thousands of deaths and great direct economic loss (Huang and Fan 2013; Cui et al. 2018b). As shown in Figure 1, the seismgenic faults are located in a transitional zone from mountains to plains. The mountains, which partly constitute the Tibet Plateau, are situated northwestward to the faults. However, the plains, which partly constitute the Sichuan Basin, are situated southeastward to the faults. Furthermore, as shown in Figures 3–5, among the above-mentioned landslides, the Daguangbao landslide with a volume of approximate 1.2 billion m³ is the biggest one, which killed 38 people. It is located in Anxian county, Sichuan province, China. Red dot lines in Figure 3 marked the boundary of the landslide. Its full length is approximate 3600 m along the main sliding direction towards N62°E and the length of the debris accumulation zone, which is located in the left and middle part of the closed red dot line marked in Figure 3, is approximate 3250 m. Apart from the above, the main steep scarp, which is located in the right part of the landslide area in Figure 3, is approximate 350 m long along the main sliding direction. The dip angle of the steep scarp is over 50°. Finally, the maximum elevation of the original slope is approximate 3000 m. a. s. l. and the minimum elevation of the original slope, where a deep valley formed, is approximate 1500 m. a. s. l. The summit of the original slope is located near the
upper-right boundary of the landslide area marked in Figure 3. Moreover, the deep valley is located near the lower-left boundary marked in Figure 3, which had been buried by the rock debris of the sliding mass.

The original slope consists mainly of carbonate rocks, phosphate rocks, coal seams and clastic rocks. In general, the lower slope consists of layered strata. The upper slope was influenced substantially by the thrust-nappe fault and some folds formed. The bottom-up strata of the lower slope include mainly Sinian dolomite, thin-bedded muddy limestone, shale and Devonian dolomite, limestone and phosphate mineral seams. The bottom-up strata of the upper slope include mainly Permian limestone, bauxite, coal seam, shale and the nappe Shuijing-Formation dolomite, interbedded bands of the siliceous rock, phyllite and killas in the Sinian System. Based on the
results of the site reconnaissance, there appeared many obvious directionally arranged scratches on the exposed sliding surface. As shown in Figure 5, the mega landslide slid to the dip-direction of the strata (Yin et al. 2011).

Based on the vertical section of the mega landslide, as shown in Figures 5 and 6, a two-dimensional numerical model was built by using UDEC software. The maximum elevation of the left boundary is 2743 m a. s. l. The maximum elevation of the right boundary is 2208 m a. s. l. Elevation of the bottom is 800 m a. s. l. The length of the bottom is 4400 m.

3.2. The constructive models and boundary conditions

With respect to their long-runout consequences, the blocks in the potential sliding mass, i.e., the left-upper blue part comprised by the quadrangular elements shown in Figure 6, were modeled as rigid blocks. The Mohr-Coulomb plasticity blocks were used to identify the response of the potential sliding bed, i.e., the black part comprised by the triangular elements. To balance the numerical accuracy and the modeling duration, the strata involved in the slope were generalized. The original slope consists mainly of sandy mudstone, dolomite, argilliferous limestone and oolitic limestone. Besides the joints between the elements in the numerical model, the bedding surfaces and the potential sliding surface are other key discontinuities. Adopted parameters of the rock strata and the discontinuities are listed in Tables 1 and 2 (Yin et al. 2011). Additionally, since the elements composing the left-upper part of the slope model are rigid bodies, all of the parameters of the Sandy mudstone and the Dolomite composing the left-upper part of the model in Table 1, except for the rock densities, are for reference only.

In the static analysis modeling, a necessary step before the subsequent dynamic analysis modeling, before the initial equilibrium under the in-situ stresses, the boundary conditions of the numerical model are x-direction fixed along the laterals and y-direction fixed along the bottom. During the following dynamic analysis after the
3.3. The dynamic input

The ground acceleration records monitored by the Qingping station in Mianzhu County, i.e., the MZQ station shown in Figure 2, were used as the uncorrected dynamic input during the numerical modeling. According to the sliding direction of the Daguangbao landslide and the 2-D numerical model, the horizontal ground acceleration record to be input along the sliding direction, i.e., NE62° was calculated based on the monitored horizontal records including the NS and EW direction. The records in the NS and EW direction were projected to the NE62° direction and summed. The value was calculated by Formula 1, i.e.,

\[
ACC_{\text{NE62°}} = ACC_{\text{EW}} \cdot \sin 62° + ACC_{\text{NE}} \cdot \cos 62°
\]  \hspace{1cm} (1)

In the formula, \( ACC_{\text{NE62°}} \) is the calculated value of the ground acceleration along the sliding direction, \( ACC_{\text{EW}} \) is the site-monitored value of the EW-direction acceleration and \( ACC_{\text{NE}} \) is the site-monitored value of the NS-direction acceleration. However, the vertical dynamic input was based directly on the monitored vertical ground acceleration. According to the empirical value of the PGA amplification (Cui et al. 2018a), the input horizontal PGA was modified to 4.615 m/s² and the input vertical PGA was modified to 3.461 m/s² as shown in Figure 7.

3.4. The results of the numerical modeling

Firstly, as shown in Figure 8d, the slope model met its critical failure after it underwent the dynamic input for 19 seconds, i.e., the running time of the model was 19 seconds. At that moment, there appeared ubiquitously open joints in the distinct element model. At the 20th second, as shown in Figures 8e and 9, the sliding mass separated thoroughly from the original slope and began to rush towards the opposite valley due to the strong ground shaking. The point A in Figure 9 indicated the separation between the sliding mass and the original slope. Moreover, as shown in Figure...
Figure 7. Acceleration records input in the distinct element numerical model.

Figure 8. Element motion states corresponding to different running time of the numerical model.
8e, at that moment, the toe of the sliding mass had collided with the opposite slope and been crushed completely. The results are in accordance with that of the site reconnaissance (Huang et al. 2012). According to the site-reconnaissance results, the mega Daguangbao landslide began to activate after the ground shaking lasted for approximate 40 seconds. The numerical model would also meet its critical failure after a 40-second seismic duration if the 20-second duration ignored after the process of the base-line correction of the site-monitored ground acceleration record was considered (Yu et al. 2009). In fact, the slight ground motion during the front 20-second can be felt by a human. And so the 40 seconds according to the site-reconnaissance is consistent with the 20 seconds duration from the original slope to its critical failure in the numerical model.

Secondly, as shown in Figure 9, from the 20th second to the 30th second, i.e., the duration corresponding to the A-B curve segment, the sliding mass experienced its first-stage long-runout motion downslope after its thorough separation from the original slope. However, the original slope underwent a backward horizontal displacement firstly, i.e., the A-A' curve segment and then a forward horizontal displacement, i.e., the A'-B curve segment.

Thirdly, as shown in Figure 9, from the 30th second to the 50th second, i.e., the duration corresponding to the B'-E curve segment, the sliding mass continued its second-stage long-runout motion until it met a peak horizontal displacement marked the point E. With respect to the original slope, or the so-called sliding bed, it continued a forward horizontal displacement until it reached an approximate zero displacement where the point D was marked.
Finally, as shown in Figure 9, from the 50th second to the 100th second, the displacement of the sliding mass converged to a constant value and so was the displacement of the original slope. During this duration, the ground shaking became less and less until it disappeared ultimately.

The whole responses of the slope under the seismic action are shown in Figure 8. Last of all, the horizontal-displacement variation of the original slope, which is shown in Figure 9, is in line with that derived from the site-monitored horizontal acceleration input, which is shown in Figure 7 (b).

4. The response mechanism of the mega landslide

The main purpose of the numerical modeling of the Daguangbao landslide is to identify the corresponding relations between the different seismic-response stages of the mega landslide and the different faulting mechanisms of the composite hypocenter. Therefore, the dynamic input for the numerical model should be a complete ground-shaking history triggered by the composite hypocenter from its initial break to terminal break. However, when the initial break of the composite hypocenter formed and the ground began to shake at Yingxiu town, the original slope at Daguangbao failed to sense the ground shaking at the same time due to its approximate 90-km distance from the initial break shown in Figure 2. According to the time lag, i.e., about 10 seconds shown in Figure 10, between the obvious ground shakings monitored by the Wolong station, about 22 km southwest to the initial break, and the Qingping station located about 82 km northeast to the initial break, the velocity of the primary wave was approximate 6 km/s. The exact locations of the Wolong and the Qingping station are shown in Figure 1. Therefore, the time lag of the ground shaking between the initial break at Yingxiu town and the Daguangbao slope was estimated to be $\frac{90}{6} = 15$ seconds. That is to say, when the original Daguangbao slope sensed the seismic wave from the initial break, the seismogenic fault had ruptured northeastward for approximate 15 seconds from the initial break.

According to the post-earthquake field investigation, the surface rupture of the Wenchuan earthquake initiated from Yingxiu town and formed gradually northeastward with an approximate 3.0 km/s velocity (Cui et al. 2018a). Due to the distance between the Daguangbao landslide and the initial break, i.e., approximate 90 km, it
took approximate 30 seconds for the surface rupture to arrive at the mega landslide. According to the results of the numerical modeling, the sliding mass separated thoroughly with the slope and began its following long runout at the 20th second. At that moment, the distance between the ongoing rupture front and the initial break was approximate \(3.0 \text{ km/s} \times (20s + 15s) = 105.0 \text{ km}\). Based on the sub-hypocenter types mentioned above, some further results on dynamic formation mechanism of the mega landslide were obtained as follows. ① On the basis of the sub-faulting mechanisms of the composite hypocenter, the progressive damage and critical failure of the mega Daguangbao landslide was triggered by the second sub-hypocenter, i.e., the sub-hypocenter triggered by the oblique-slip fault involving a dominant reverse component. ② According to the other classification basis, i.e., the location of the Daguangbao landslide modeled, its progressive damage was induced by the Approaching Hypocenter, i.e., the \(b-c\) line segment in Figure 2, and the Local Hypocenter, i.e., the \(c-d\) line segment in Figure 2, chronologically. The Local Hypocenter triggered its critical failure.

The further corresponding relations are shown in Tables 3 and 4. The results in the tables show the relations between the different dynamic response stages of the landslide and the actions of the different sub-hypocenters clearly.

According to the numerical results shown in Figure 9, Tables 3 and 4, from the 20th second to the 50th second of the model running time, the sliding mass experienced a long-runout rush. The long runout included the dramatic ejection, collision and crushing of the sliding mass. Due to the low friction, even few contacts among the elements composing the sliding mass during its collision and crushing, the
Table 3. Dynamic formation mechanisms of the Daguanbao landslide triggered by the different sub-hypocenters based on the corresponding faulting mechanisms.

| Sub-faulting mechanism | Length of rupture | Rupture duration / s | Dynamic response of the mega landslide | Seismic action duration on the landslide/s | Distance of the rupture front from the initial break/km | Sub-hypocenter which acts on the landslide |
|------------------------|------------------|----------------------|------------------------------------------|------------------------------------------|--------------------------------------------------|------------------------------------------|
| The first sub-faulting/Reverse faulting | ≈30 km | 0~10 | No | No | ≈30 | No |
| From the initial break to Wenchuan county | | | | | | |
| The second sub-faulting/the oblique-slip faulting | ≈90 km | 10~15 | Progressive damage | 0~19 | ≈45 | The second sub-hypocenter |
| From Wenchuan county to Maoxian county | 15~34 | Critical failure | 19~20 | ≈102 | |
| 34~35 | Long runout, including ejection, collision and crushing | 20~25 | ≈120 | | |
| 35~40 | | | | | | |
| The third sub-faulting/the oblique-slip faulting | ≈70 km | 40~63 | 25~48 | ≈190 | | Self-gravity mainly, the third sub-hypocenter to a minor extent |
| From Beichuan county to Pingwu county | | | | | | |
| The fourth sub-faulting/the strike-slip faulting | ≈110 km | 63~65 | 48~50 | ≈195 | | Self-gravity mainly, the fourth sub-hypocenter to a minor extent |
| From Pingwu county to Qingchuan county | 65~100 | Accumulation | 50~85 | ≈300 | | |
| Sub-hypocenter          | Distance range of the rupture front from the initial break/km | Rupture duration /s | Dynamic response of the mega landslide | Seismic action duration on the landslide /s | Distance of the rupture front from the initial break / km | Sub-hypocenter which acts on the landslide |
|------------------------|-------------------------------------------------------------|---------------------|-----------------------------------------|---------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Initial Hypocenter     | −15 ~ 15                                                   | 0 ~ 5              | No                                      | No                                         | ≈15                                             | No                                            |
| Approaching Hypocenter | 15 ~ 45                                                    | 5 ~ 15             | No                                      | No                                         | ≈45                                             | The Approaching Hypocenter                   |
| Local Hypocenter       | 45 ~ 75                                                    | 15 ~ 25            | Progressive damage                      | 0 ~ 10                                      | ≈75                                             | The Local Hypocenter                         |
|                        | 75 ~ 102                                                   | 25 ~ 34            | Critical failure                        | 10 ~ 19                                     | ≈102                                            |                                               |
|                        | 102 ~ 105                                                  | 34 ~ 35            | Long runout, including ejection, collision and crushing | 19 ~ 20                                     | ≈105                                            |                                               |
| Receding Hypocenter    | 105 ~ 195                                                  | 35 ~ 65            | Accumulation                            | 20 ~ 50                                     | ≈195                                            | Self-gravity mainly, the Receding Hypocenter to a minor extent |
|                        | 195 ~ 270                                                  | 65 ~ 90            |                                        | 50 ~ 75                                     | ≈270                                            |                                               |
| Terminal Hypocenter    | 270 ~ 300                                                  | 90 ~ 100           |                                        | 75 ~ 85                                     | ≈300                                            | Self-gravity mainly, the Terminal Hypocenter to a minor extent |
seismic forces could hardly influence all the elements. Therefore, the self-gravity rather than the seismic forces posed a key influence on the elements composing the sliding mass. However, the coupling between the seismic inertial force and the self-gravity posed a key influence on the sliding mass during its ejection. Moreover, on one hand, the long runout was also influenced by the second sub-hypocenter, the third sub-hypocenter and the fourth sub-hypocenter to a minor extent. On the other hand, i.e., with respect to the classification basis of the composite hypocenter considering the location of the landslide, the long runout was also influenced to a minor extent by the Receding Hypocenter.

Finally, from the 50th second to the approximate 85th second, the sliding mass began to accumulate due to the local topography. This response stage was controlled mainly by the self-gravity for the abovementioned reason, i.e., the low friction, even few contacts among the elements composing the sliding mass and the hardly effective seismic forces. However, on one hand, the action of the fourth sub-hypocenter influenced this motion to a minor extent. One the other hand, the Receding Hypocenter and the Terminal Hypocenter influenced this motion of the sliding mass to a minor extent chronologically.

The above results shown in Tables 3 and 4 could be obtained easily based on the time corresponding presented in the above tables.

5. The key-controlling mechanical factors

According to the numerical results shown in Figure 9, during the progressive damage and critical failure of the mega landslide, i.e., in the initial 20 seconds, the maximum horizontal displacement of the whole slope reached approximate 160 m. However, in the same time duration, the maximum vertical displacement was only approximate 30 m. Therefore, the horizontal seismic force posed a key contribution to the dynamic responses of the slope during this period. Moreover, on one hand, the second sub-hypocenter generated the horizontal seismic force if the sub-faulting mechanism was considered. On the other hand, the Approaching Hypocenter and the Local Hypocenter generated chronologically the horizontal seismic force if the location of the mega landslide was considered. Further results, which could be obtained easily based on the time corresponding between the different response stages of the landslide and the actions of the corresponding sub-hypocenters, are shown in Table 5.

Secondly, as shown in Figure 9, from the 20th second to the 50th second, due to the longer horizontal displacement than the vertical displacement of the sliding mass, the self-gravity mainly controlled the dynamic responses during this period besides the local topography due to the low friction, even few contacts among the elements composing the sliding mass and the hardly effective seismic forces. The inertial seismic force also contributed the ejection largely. Furthermore, the horizontal seismic force also controlled the responses to a minor extent. On one hand, the second, the third and the fourth sub-hypocenter generated the horizontal seismic force chronologically. On the other hand, the Receding Hypocenter generated the horizontal seismic force when the location of the mega landslide was considered.
Table 5. Controlling mechanical factors corresponding to different response stages of the landslide.

| Dynamic response of the mega landslide | Rupture duration/ s | Sub-hypocenter | Seismic action duration on the landslide /s | Key controlling mechanical factors |
|----------------------------------------|---------------------|----------------|-------------------------------------------|-----------------------------------|
| No                                     | 0 ~ 5               | The first/Reverse faulting | Initial Hypocenter | No |
|                                        | 5 ~ 10              | Approaching       | 0 ~ 10                      | The horizontal seismic force |
|                                        | 10 ~ 15             | The second / the oblique-slip faulting | Approaching | No |
| Progressive damage                     | 15 ~ 25             | Local Hypocenter | 10 ~ 19                     | Self-gravity mainly, instantaneous inertial seismic forces, the horizontal seismic force triggered by the corresponding sub-fault / sub-hypocenter to a minor extent |
| Critical failure                       | 25 ~ 34             | Receding Hypocenter | 19 ~ 20                     | |
| Long runout, including ejection, collision and crushing | 35 ~ 40 | The third / the oblique-slip faulting | Receding Hypocenter | 20 ~ 25 |
|                                        | 40 ~ 63             | 25 ~ 48          | Self-gravity mainly, the coupling of the horizontal and vertical seismic force triggered by the corresponding sub-fault / sub-hypocenter to a minor extent |
|                                        | 63 ~ 65             | The fourth / the strike-slip faulting | Terminal Hypocenter | 48 ~ 50 |
| Accumulation                           | 65 ~ 90             | 50 ~ 75          | Self-gravity mainly, the coupling of the horizontal and vertical seismic force triggered by the corresponding sub-fault / sub-hypocenter to a minor extent |
|                                        | 90 ~ 100            | 75 ~ 85          | |

2186 F. CUI ET AL.
Finally, as shown in Figure 9, from the 50th second to the 85th second, the self-gravity controlled mainly this dynamic response, i.e., the accumulation of the sliding mass, besides the local topography due to the low friction among the elements composing the sliding mass. Furthermore, the coupling of the horizontal and vertical seismic force contributed the dynamic response to a minor extent. On one hand, the coupling force was generated by the fourth sub-hypocenter when the faulting mechanism was considered. On the other hand, the Receding and Terminal Hypocenter also contributed the coupling force chronologically based on the other classification basis of the composite hypocenter.

The above is a great improvement based on related researches (Cui et al. 2018a).

6. Discussion

Based on the results of the above numerical modeling, the composite property of the hypocenter and its influence to the original slope were fully illustrated. Firstly, according to two classification bases, i.e., different faulting mechanisms of the hypocenter and spatial location of the modeled landslide, the composite nature of the hypocenter was explored completely. As a result, the composite hypocenter was divided into different sub-hypocenter for the first time. However, realistic significance of the second classification factor is necessary to be verified furtherly and the factor should be refined. In a sense, the composite nature of the hypocenter is what we emphasize and its detail should be discussed furtherly. Secondly, influences of the different sub-hypocenters, which induced different responses, i.e., the progressive deformation, the critical failure, the long run-out, et al, of the Daguangbao landslide were identified for the first time. For example, the progressive deformation and critical failure of the mega landslide were triggered by the second sub-hypocenter according to the classification basis of the sub-faulting mechanism. As for the mechanical impact, the continuous horizontal seismic force, which was induced by the second sub-hypocenter, contributed mainly the progressive deformation and critical failure. The horizontal seismic force caused the tensile vertical fracture located in the upper left part of the original slope shown in Figure 8e firstly and then the critical failure of the whole slope gradually. Furthermore, when the mega landslide experienced its post-failure responses, i.e., the long runout of the sliding mass, the seismic forces that were caused by the third and the fourth sub-hypocenter could hardly control the responses in this stage intensively because of the thorough separation and low cohesion between the sliding mass and the original slope. That is to say, self-gravitation of the sliding mass and local topography nearly controlled the long run-out of the landslide. However, during the first stage of the long run-out, i.e., the ejection of the sliding mass, the dynamic response was also influenced by the inertia seismic force because of the initial acceleration of the sliding mass.

In fact, as for formation mechanism of earthquake-induced landslides, lots of researches are conducted and many results are obtained in these years (Keefer 2002; Chigira et al. 2003; Biondi et al. 2004; Chernouss et al. 2006; Chigira and Yagi 2006; Meunier et al. 2008; Jibson 2011; Strenk and Wartman 2011; Meunier et al. 2013; Del Gaudio et al. 2014; Gorum et al. 2014; Rizzitano et al. 2014; West et al. 2014; Gallen...
et al. 2015; Basharat et al. 2016; Fan et al. 2016; Grant et al. 2016; Saade et al. 2016; Chang et al. 2017; Croissant et al. 2017; Hartzell et al. 2017; Hu et al. 2018; Nowicki Jessee et al. 2018; Roback et al. 2018; Fan et al. 2019). Among these results, such factors as local topography, lithology, rock mass structure & tectonics, ground water and seismic force were fully discussed. However, composite property of a seismogenic fault, especially its composite influence to contribute a landslide was seldom studied. As a matter of fact, related researches are urgent and necessary, especially to many landslides triggered by the strong Wenchuan earthquake with a composite hypocenter, should be focused intensively.

Last of all, to obtain a more comprehensive result on failure mechanisms of the numerous typical landslides triggered by the composite hypocenter, more case studies should be conducted. However, well begun is half done. More landslides along the seismogenic faults are urgent to be modeled. We hope indeed the results we obtained could integrate formation mechanism of similar coseismic landslides from a new aspect.

7. Conclusion

1. Based on the sub-faulting mechanism of the strong Wenchuan earthquake, the whole composite-hypocenter is divided into four sub-hypocenters. Towards the main direction of the seismogenic fault evolution, the first sub-hypocenter is triggered by the reverse-slip fault. The second sub-hypocenter is triggered by the oblique-slip fault involving a dominant reverse component. The third sub-hypocenter is triggered by the oblique-slip fault involving nearly equal components of reverse and strike-slip motion. The fourth sub-hypocenter is triggered by the strike-slip fault. With respect to the other classification basis, the composite-hypocenter is divided into the Initial Sub-hypocenter, the Approaching Sub-hypocenter, the Local Sub-hypocenter, the Receding Sub-hypocenter and the Terminal Sub-hypocenter simultaneously according to the location of the mega landslide modeled.

2. The progressive damage and critical failure of the mega landslide are triggered by the second sub-hypocenter, i.e., the one triggered by the oblique-slip fault involving a dominant reverse component. At the same time, its progressive damage is induced by the Approaching Sub-hypocenter and the Local Sub-hypocenter chronologically. The Local Sub-hypocenter triggers its critical failure.

3. During the long-runout and accumulation responses of the sliding mass, its self-gravity poses a dominant contribution to the dynamic responses besides the local topography. The inertial seismic forces also contribute the ejection response largely of the sliding mass. The following seismic forces triggered by the corresponding sub-hypocenter influence the long runout and accumulation responses of the sliding mass to a minor extent.

4. The horizontal seismic force poses a dominant contribution to the progressive damage and critical failure of the Daguangbao slope. On one hand, the second sub-hypocenter generates the horizontal seismic force when the faulting mechanism is considered. On the other hand, the Approaching Sub-hypocenter and the Local Sub-hypocenter generate chronologically the horizontal seismic force when the location of
the mega landslide is considered. The Local Sub-hypocenter generates the horizontal seismic force, which triggers the critical failure of the sliding mass.

The dynamic responses of the mega landslide triggered by the strong earthquake include the progressive damage, the critical failure, the long runout and the accumulation respectively. The long runout includes the ejection, the collision and the crushing of the sliding mass, respectively.

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