Invited Commentary

Amplification Mechanism and Hazard Analysis for Zhouqu Giant Debris Flow

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A giant debris flow occurred in Zhouqu County, Gannan Tibetan Autonomous Prefecture, Gansu Province, in the evening of 7 August 2010, causing 1765 deaths and missing, with enormous property losses. It ruined 4321 houses and caused 22,667 homeless. The stricken area at Sanyanyu debris flow was 50.0 hm² including 3 hm² urban area and 47 hm² farmland. A dammed lake 2 km in length was formed in Bailongjiang River by the debris flow deposit with 8-10 m high, which blocked the river. The main urban area of Zhouqu city was inundated for one month. This tragic catastrophe raises a topic that how a giant debris flow develops from a relatively small original one in source area and what methodology can be used to identify whether a building is in danger or not. In order to understand this issue, a detailed field survey had been carried out in catchments of Sanyanyu and Loujiayu. The field survey revealed that flood in upstream eroded the debris barriers and unconsolidated soil bed in channel and developed into debris flow. The laboratory physical experiments indicated that the major mechanism of giant natural debris flows formation is scale amplification caused by cascading landslide dam failures. Another process of scale amplification is that debris flow schleps sediment from erodible channel bed. At last, a numerical technique will be developed to simulate danger area and momentum of debris flow. Based on the results of dynamic simulation, a method of hazard assessment will be established for identifying dangerous area. Hope this methodology can serve for urban management in mountainous villages and townships.

Key words: giant debris flow, formation mechanism, scale amplification, hazard analysis

1. INTRODUCTION

Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction [Iverson, 1997]. Solid material and water are the vital factors of debris flow formation. Normally, debris flow is triggered by abundant supply of water, either from rain storm or snow melting. The large amount of solid material supply for debris flow could come from multiple resources, such as landslide, avalanches, slope erosion etc. It is noted that landslides are usually the dominant mechanism for conveying large amounts of debris to river channels [Korup et al., 2004]. Therefore, the same mechanism will provide overwhelming supply of solid material when the landslide is along the channel. Studies have reported that large landslides inundate river valleys and overwhelm channels with large volumes of coarse materials, commonly forming stable landslide dams that trigger extensive and prolonged aggradations upstream [Ouimet et al., 2007]. The largest and most devastating debris flows originates in a small scale and continually amplified by eroding mobile channel bed and collecting masses and flows from tributaries and slopes [Cui, 1992]. The debris barrier outburst is another reason for the generation of large magnitude debris flow [Cui et al., 2013a]. Debris barrier is an accumulation of debris in the channel which caused partial or complete blockage of channel. The debris may result from landslide, shallow slope failure or previous debris flow residual. Therefore, debris barrier also may be referred as landslide dam when the debris comes from landslide. In mountainous area, when there is excessive supply of water, flash flood could be developed upstream and have the capability to carry huge amount of debris downstream. With the present of large amount of debris in the channel, the flash flood could entrain the debris and transform into debris flow.
Fig. 1 Sequential air photography showing massive aggradation on the lower town and Bailong River following the Zhouqu debris flow on Aug. 8, 2010. (Image from Cui et al. [2013b].)

(a) The satellite image shows the gully morphology
(b) Locations of the landslide dams and sections of field investigation along Dayu Gully;
(c) Locations of the landslide dams and sections of field investigation along Luojiayu Gully;
(d) Zhouqu township located on the deposited fans (the area bracketed by d1-d2 and A'-A”). Image courtesy of the Chinese State Bureau of Surveying and Mapping

When debris flow reaches human settlements, it usually results as tragedy. Different from avalanches and landslide, debris flows behavior is governed by the interaction of the fluid and solid grain force, which gives debris flow a unique signature: it can travel a long distance with very high speed along the channel, as fluid. At the same time, it holds enormous energy and cause huge damage, as avalanche. A catastrophic debris flow struck Zhouqu, Gansu Province of China on 7 August 2010, causing 1,765 deaths and missing, with enormous property losses. Intense rainfall triggered flash flood upstream. When the flood rushed down in the valley channel, it crashed the landslide dams in the channel and the entrainment of dam debris transformed the flood into debris flow.

Multiple collapsed landslide dams were spotted along the channel after the disaster. Thus, we can postulate that incoming streams may have caused cascading landslide dam failures. During the process, the magnitude of the debris flow is believed to have significantly increased because of the failure of those landslide dams, as the geography downstream consists of steep canyons with easily erodible granular materials that can be entrained into the flow and can increase flood peaks. There are many case studies of individual natural-dam failure [e.g., Costa and Schuster, 1988; Korup et al., 2004], but an integrated view of the cascading failure of clusters of landslide dams falling like dominoes along the slope channels have not been discussed so far. The mechanism underlying such failure process, and the resulting debris flow discharge variation are still not clear.

The Zhouqu debris flow ruined 4,321 houses and caused 22,667 homeless. A dammed lake 2 km in length was formed in Bailongjiang River from the debris flow deposit with 8~10 m in height, which blocked the river. The main urban area of Zhouqu city was inundated for one month. This devastating event have raised question on how to quantitatively assess the hazard level of debris flow prone areas. With the 5–10 years of active period of natural hazard after Wenchuan earthquake in western China [Cui et al., 2011a], the demand of hazard analysis is roofing. In order to put forward an effective hazard assessment method, the scale amplification mechanism of debris flow due to the cascading collapse of blockage along debris channel was investigated. A physical experiment has been carried out in order to capture the discharge increment due to such effect. Numerical simulation has been used to extract the dynamic parameters of debris flow movement. Eventually, dynamic based hazard assessment method is developed to identify the hazard level of alluvial fan or debris flow affected area.

2. THE ZHOUQU DEBRIS FLOW EVENT

In the evening of 7 August 2010, two debris flows struck Zhouqu County at the same time which ruined 4,321 houses and caused 22,667 homeless. Debris flows occurred in two large gullies, Sanyanyu Gully and Luojiayu Gully both of
which intersect at Zhouqu County. The affected area from Sanyanyu gully debris flow was 50.0 hm² including 3 hm² urban area and 47 hm² farmland. The Sanyanyu Gully is further subdivided into two large gullies, Dayu Gully and Xiaooyu Gully, which converge at the point “O” in Fig. 1(a). The urban area of Zhouqu Township located on the debris fan (Fig. 1(a), 1(d)) was mostly wiped out after the giant debris flow event.

The debris flows thrusted through the county, destroyed all buildings along its path, interrupted electric power, communications, and water supply, then rushed into the Bailong River and formed a dammed lake.

Many studies have looked at the reasons behind the giant Zhouqu debris flows [e.g., Hu et al., 2010; Ma, 2010; Yu, et al., 2010; Fang et al., 2010]. Most considered the debris flows that occurred in the Sanyanyu Gully prior to the giant event to be non-viscous debris flows. Luojiayu Gully showed a low frequency of debris flow occurrence, and no debris flow have occurred in the past decades. The watershed of Sanyanyu Gully is about 25.75 km, stretching from north to south and shaped like a “gourd dipper.” The length of the main gully is about 9.7 km, with the highest and lowest elevations being 3828 m and 1340 m, respectively, and possessing a mean gradient of 24.1%. The watershed of Luojiayu Gully is about 16.60 km², and is shaped like a “calabash.” The length of the main gully is about 8.5 km, and the elevation changes from 3794 m to 1330 m with a mean gradient of 23.9%. Tributaries along the gullies are well developed and streams can be observed in Sanyanyu Gully, which has permanent stream while Luojiayu gully has ephemeral stream. Due to the intense incision and erosion, most valleys in the gully are “V” shaped. Many landslide dams were found distributed along the narrow gullies before the debris flow event, impounding an abundance of sediment. Debris flows are mostly triggered by the failure of these landslide dams caused by upland flash floods.

3. FIELD INVESTIGATION

To understand the evolution process of Zhouqu debris flow, field investigation was carried out. The Luojiayu Gully were carefully measured and analyzed, including channel width, flow height, roughness of the slope bed, and landslide dam size and geometry. Furthermore, the locations of the landslide dams along the channels were recorded using GPS, allowing analysis of the distribution of landslide dams in the gullies. As shown in Fig. 1(a), beyond point DG and LG, few landslide dams were spotted on site. Therefore, the investigation has been focus on regions highlighted with dash line in Fig. 1(a) where we believe the flash flood have transformed into debris flow when it passed through these regions.

To estimate the flow discharge and derive debris flow evolution process along the sloping channels, the most widely used hydraulic formula, the Manning equation, was applied. Two widely applied semi-empirical formulas for the estimation of discharge and velocity of debris flows were also used for comparison. Fig. 1(b), 1(c) illustrate the locations of the chosen cross sections for measurement (yellow line in Fig. 1(b), 1(c)) and distributions of the landslide dams (green dots in Fig. 1(b), 1(c)) along the channels for Dayu Gully and Luojiayu Gully, respectively. All the landslide dams along the channel were found breached and we conjected a cascading failure of those landslide dams occurred during this event. This cascading failure process was verified by conducting physical experiment.

Our field investigation measured the dimensions of the landslide dams, the channel’s cross-sectional area and gradient in the Luojiayu and Sanyanyu gullies. Assuming that the debris flows which occurred in Zhouqu were uniform steady flows, the velocity U and discharge Q can be calculated according to Manning’s formula:

\[ Q = - \frac{1}{n} \cdot A \cdot R_n^{2/3} \cdot \sqrt{J} \]  
\[ U = \frac{Q}{A} \]  

(1)  
(2)

where, \( A \) is the cross-sectional area, \( R_n \) is the hydraulic radius, \( J \) is the channel bed gradient, and \( n \) is the Manning roughness coefficient. The values of \( A, R_n, \) and \( J \) were directly measured in the field investigation. Manning roughness coefficient for debris flows is approximately evaluated in this paper according to the research work of Xu and Feng [1979]. Two other empirical formulas which are widely used in China were applied to compare the calculated flow discharge.

The first one is referred to as the Wudu method. Similarities in the lithology of the solids and in flow type between the debris flows which occurred in both Wudu and Zhouqu makes the Wudu method highly recommended for estimating the discharge of the Zhouqu debris flows.

\[ Q = \frac{1}{n_c} \cdot A \cdot H_c^{2/3} \cdot \sqrt{J} \]  

(3)

Where, \( H_c \) is the debris-flow depth and \( n_c \) is the roughness coefficient for viscous debris flows. An empirical equation was developed for the estimation of \( n_c \) [Yang, 1985].
The other formula for the velocity/discharge estimation of debris flows based on the Chezy model is recommended by [Lo, 2000] and “The Specification of Geological investigation of Debris Flow Stabilization” [DZ/T 0220-2006] published by the China Ministry of Lands and Resources (CMLR) [Tang et al., 2011].

\[ \frac{1}{n_c} = 18.5H^{-0.42} \]  

\[ Q = K_c \cdot A \cdot H_c^{2/3} \cdot J^{1/5} \]

\( K_c \) is a factor that is related to debris flow depth according to Table 1.

3.1 Variation in flow velocity and discharge along Luojiayu Gully

Luojiayu Gully has been taken as an example to show the results of our field investigation and elaborated with our findings. As shown in Fig. 2, the flow discharge calculations using the three different methods are generally consistent, and the values are quite close to one other. There exist six obvious debris flow scale amplification phases (i.e., A-B-C, E-F, I-J, K-L-M, Q-R, U-V-W-X) between point LG and the downstream mouth of Luojiayu Gully, as shown in Fig. 2 (the peak points include C, F, J, M, R and X). The variation in debris flow discharge along the gully indicates that the magnitude increase of the debris flow may have attributed to the cascading failure of landslide dams in the gully. The phase U-V-W-X represents the scale increase of the debris flow due to erosion of the channel bed. At this section, the channel is narrowing down and the debris flow speed significantly increases, which could easily erode sediments on the channel bed which entrained by the upstream flows. Channel bed degradation with armoring was also observed, with an estimated erosion depth of 2–3 m.

However, the magnitude of the debris flow decreases when the channel morphology widens or curves because the reduced flow velocity induces large amounts of sediment to deposit on the channel bed. There are two phases (C-D and O-P) where discharge of the debris flow in Luojiayu Gully decreases. Between C-D, there are two big bends in the sloping channel. The debris flow mostly moved through the curved channel with gradually reduced velocities. A large amount of sediment in the flow deposited at the bends, reducing the scale of the debris flow. The O-P phase represents when the debris flow moved through a gradually broadening section, depositing a large volume of sediment. This resulted in a decrease in debris flow scale.

4. MECHANISM OF SCALE AMPLIFICATION FOR DEBRIS FLOW

Debris flow motion involves a cascading of energy that begins with incipient slope movement and ends with deposition. The trigger and formation of debris flow through cascading landslide dam failures can also be interpreted from an energy point of view: Landslide dam failures and the formation of downstream flow are a process of energy transform from potential energies of reserved water to bulk kinetic energies. Once the break in the landslide dam occurs, huge potential energy of reserved water can transform into a large kinetic energy of strong flow waves.

Following the breach of a landslide dam, the solid materials of the dam (including the reserved granular particles behind the landslide dam) are mostly mobilized and contribute to the developed flows. The additionally entrained solids in the water increase the flow density. The most important issue is that the sediment concentration increases as the flow type changes from a pure water flow, to a stream flow with solids transport, then to a hyper-concentrated flow, and finally a debris flow (or even a landslide or debris avalanche) [Coussot and Meunier, 1996]. The floods resulting from the failure of natural dams are, in most cases, much larger than floods originating directly from snowmelt or rainfall.

Geomorphology of the sloping channels
significantly influences energy release and transformation. Curved sloping channels and steep inclines can greatly affect flow dynamics, which can further affect the energy and mass exchange between debris flows and the sloping channels.

In order to understand the phenomena of debris-flow scale amplification resulting from cascading landslide dam failures, physical experiments were carried out in large flumes to capture the key modes of cascading landslide dam failure (Fig. 3). The hydrodynamic process of cascading landslide dam failures due to upstream (debris) flows was modeled.

To construct a model to describe the amplification effect of landslide dam, dimensionless factors which describing the characteristic of landslide dam and dynamic condition. \( H/H_r \) was dimensionless dam height and could reflect the water head; \( V^{1/3}/H \) represent the outburst discharge; \( V_d^{1/3}/H \) describes the mass provided during the dam breach [Peng and Zhang, 2012]. The erosion and sediment transport capacity was described using:

\[
\Theta = \frac{\gamma_f h J}{(\gamma_s - \gamma_f) d_{50}}
\]  

(6)

where \( \gamma \) is the ratio of density of the debris flow to water and \( H_r \) is the total hazard degree; \( \gamma_r \) is the hazard degree caused by the impact of debris flow to maximum kinetic energy value at any affected area during the whole debris flow movement process; \( D_r \) is the hazard caused by debris flow deposition indexed to ratio of debris flow to the maximum flow depth during the process.

5. DYNAMIC BASED HAZARD ANALYSIS METHOD

With the understanding of the mechanism of scale amplification, the next question is how to assess the hazardous level imposed by debris flow based on it movement process. A debris flow simulation method was firstly described in this section together with a method of quantitatively determining the hazard level from debris flow impact and siltation.

5.1 Qualitative hazard assessment model

A quantitative but handy hazard analysis model is proposed as below [Cui et al., 2013a]:

\[
D = D_r + D_b
\]  

(9)

where, \( D_r \) is the total hazard degree; \( D_r \) is the hazard degree caused by the impact of debris flow to maximum kinetic energy value at any affected area during the whole debris flow movement process; \( D_b \) is the hazard caused by debris flow deposition indexed to ratio of debris flow to the maximum flow depth during the process.

5.2 Impaction hazard and inundating hazard calculation

We can simulate the debris flow movement process in an alluvial area by adopting the numerical approach, using the DEM of the studied area to identify the spatial distributions of velocity and flow depth for each grid square during the movement process.

In order to quantitatively characterize the largest impact hazard at each position, we represent the damage capability of a debris flow by the maximum kinetic energy. This process allows us to calculate the energy of each grid square for the entire dynamic debris flow process. The impact energy is calculated as below:

\[
H_r = A \cdot \max \left[ (u^2 + v^2)h \rho \right]
\]  

(10)

where \( Q \) is peak discharge during dam breaching, \( Q_b \) is the discharge of upstream flow, \( H_d \) is the dam height, \( V_d \) is the volume of the dam, \( H_r \) is the length of dam, \( k \) is the scale amplification coefficient of peak discharge.
where $H_e$ is the maximum value of the kinetic energy of the debris flow (N·m), $u$ and $v$ are the velocities (m/s) in the $x$ and $y$ directions, respectively, $h$ is the flow depth (m), $\rho$ is the density of the debris flow (t/m³), and $A$ is the grid area (m²). $N_{n,j}$ is the number of particles on grid at time $n$ and $u_k, v_k$ are the velocities (m/s) for the $k$-th particle on grid $(i, j)$, respectively. The larger value of $H_e$ indicates the higher hazardous level.

On the other hand, in order to determine silting damage, the maximum flow depth of the debris flow is adopted to index the silting hazard. The flow depth of each grid can be calculated using the following formula:

$$ H_h = \max(h) = \frac{N_{n,j} \Delta V}{A} $$

where $N_{n,j}$ is the number of particles on grid $(i, j)$ at time $n$, $\Delta V$ is the average volume of each particle (m³), $A$ is the grid area (m²), $h$ is the flow depth (m), and $H_h$ is the silting degree or maximum flow depth (m). Generally, larger values of $H_h$ represent a severer hazard. In order to calculate the value of $H_h$, we assumed the depth of the deposition as the accumulation of sequential debris flows. Therefore, we can identify the deposition range and the thickness of each debris flow in the same coordinate system.

5.3 Numerical approach - debris flow movement

Numerical approach is the most effective tools to analysis debris flow process and extracts the flow velocity and flow depth which are the parameters required for hazard assessment as described in section 5.2. After understanding the amplification mechanism of debris flow due to cascading dams’ failure along the channel, the flow discharge can be estimated as the initial condition for a numerical simulation. Flow velocity is a key parameter for identifying the impact force of a debris flow, while the flow depth can reflect the silting hazard [O’Brien et al., 1993; Rickenmann, 2001; Wei et al., 2006]. The debris flow motion equation includes three important variables: mud depth, the $x$-velocity component, and the $y$-velocity component.

$$ \frac{Du}{Dt} = gS_{xs} - gS_{fx} $$
$$ \frac{Dv}{Dt} = gS_{sy} - gS_{fy} $$

Here, $u$ and $v$ are $x$-component and $y$-component velocities respectively (m/s), $g$ is acceleration due to gravity (m/s²), $S_{xs}$ is the bottom slope of the deposition area in the $x$-direction ($°$), $S_{sy}$ is the bottom slope of the deposition area in the $y$-direction ($°$), $S_{fx}$ is the friction gradient of the debris flow in the $x$-direction ($°$) and $S_{fy}$ is the friction gradient of the debris flow in the $y$-direction ($°$).

According to O’Brien’s equations [O’Brien, 1993], $S_{fx}$ and $S_{fy}$ can be calculated using:

$$ S_{fx} = \frac{\tau_{h}}{\gamma_m \delta} \text{sgn}(u) + \frac{2\mu_h u^2}{\gamma_m h^2} + \frac{k_v \sqrt{u^2 + v^2}}{gh} $$
$$ S_{fy} = \frac{\tau_{h}}{\gamma_m \delta} \text{sgn}(v) + \frac{2\mu_h v^2}{\gamma_m h^2} + \frac{k_v \sqrt{u^2 + v^2}}{gh} $$

where $\tau_{h}$ is the yield stress (N/m²), $\gamma_m$ is the density of the debris flow (t/m³), $h$ is the flow-depth (m), $\mu_h$ is the viscous coefficient (N.s/m²), and $\delta$ is the roughness coefficient.

To solve Eq. (12) numerically, Hu and Wei [2005] improved the particle model originally developed by Wang et al. [1997], while Cui et al. [2011b] discussed the method and approximated the debris flow movement by using the forward difference for each particle. The model treats debris flow masses as aggregates of many small particles, each of which has its own mass and velocity. The differential equations can thus be expressed as
\[
\frac{u_k^{n+1} - u_k^n}{\Delta t} = gS_{xx}^{n,k} - gS_{xx}^{n,k}, \\
\frac{v_k^{n+1} - v_k^n}{\Delta t} = gS_{sy}^{n,k} - gS_{sy}^{n,k}
\]

where \(u_k^{n+1}, v_k^{n+1}\) are the values of \(u\) and \(v\) for the \(k\)-th particle at time \(n+1\), respectively, and \(u_k^n, v_k^n, S_{xx}^{n,k}, S_{xy}^{n,k}, S_{sy}^{n,k},\) and \(S_{yy}^{n,k}\) are the values of \(u, v, S_{xx}, S_{xy},\) \(S_{sy},\) and \(S_{yy}\) for the \(k\)-th particle at time.

Particle movement can be traced using the MAC (marker-and-cell) computational technique [Hu and Wei, 2005]. A digital elevation model (DEM) grid of the real topography of the debris flow gully is generated using GIS, and provides division of the computational cells. Therefore, each grid has a value for flow depth, velocity, and elevation.

For the accuracy of numerical simulation, the input of initial condition is critical. The initial flow rate and flow velocity must be calculated correctly. To achieve this, the formula (8) in section 4 derived from our experiment are adopted to capture the scale amplification effect on the debris flow discharge. The parameters in the formula such as volume and height of dams in the channel are measured from our field investigation. The simulation results of Zhouqu debris flow is shown in Fig. 4 which presented the difference of simulated and actual affected area together with the flow height. Considering the fact that field investigation might not be feasible in some regions, remote sensing interpretation using high definite satellite image could also be used in calculating such parameters.

6. CONCLUSION

Debris flow could originate in small scale at the formation region and travel very far along the sloping channel and the scale could increase dramatically. Our investigation at Zhouqu has revealed one kind of the evolution of debris flow. Firstly, a series of landslide dams created by intense earthquakes, which completely or partially blocked sloping channels before debris flow events, are quite common in natural mountainous areas. Once the failure of an upstream landslide dam occurs, a cascading failure of landslide dams further downstream will likely take place. This hazardous process can begin many kilometers upstream of the deposition fan and, through a complex cascade of geomorphic events, can lead to catastrophic discharge at downstream locations.

The whole process of cascading landslide dams failure and flood scale amplification is a transformation from reserved potential energy to bulk kinetic energy of the flow, together with mass entrainment of granular material on the sloping bed into the debris flow. Depending on the evolution analysis, the peak discharge of the hazardous process can exceed that of infrastructure designed to withstand floods (typically a 50 to 200 years flood return period) by a factor of 2 to 50 [Cui et al., 2013b]. Our experiment has put forward new models to calculate the scale enlargement of debris-flow peak discharge that accounts for cascading landslide dam failure and entrainment of sediment materials.

The giant debris flow in Zhouqu has raised the concern on the risk assessment method. Traditional methods for hazard and vulnerability assessment which are mostly based on experts’ judgment and historical events regression are not able to satisfy the raising demands. This paper focused on hazard assessment and has developed a systematic method to evaluate the threat of debris flow to its affected area, i.e. the alluvial fan. A numerical simulation is used to simulate debris flow movement. Based on different mode of damage caused by debris flow, a hazard assessment method based on flow energy and flow height is explored. The simulation result could be used to extract the parameter required in the hazardous assessment.

With the support of a debris flow numerical simulation, remote sensing (RS), and GIS techniques, we developed a systematic and quantitative method of hazard assessment for mountain towns.

This phenomenon of cascading landslide dam failure and scale amplification mechanism is quite complicated, and still not yet fully understood. Our current study has preliminarily revealed the relationship between the channel blockage and the discharge variation of debris flow. However, the variety of landslide dams is not accounted in our experiment and the regression formula also does not carry specific physical meaning. Therefore, this formula should be verified by more events before adopting any engineering design. Moreover, there are other causes which need to be considered for the discharge increment, for example the channel bed and side wall erosion during debris flow movement in the channel. Some researcher started to incorporate the erosion process in the debris flow simulation [Ouyang et al., 2015], further study shall be carried out on the mass exchange process between the mobile bed and debris flow.

Although debris flow travels relatively slowly
at the alluvial fan area, the exchange of bed sediment with debris flow still should be accounted for. The new flow model incorporating the mass exchange should be developed when simulating the debris flow movement and improve the hazard assessment.

This paper deals with only the hazard assessment. This is just one pillar for risk assessment, which is the ultimate goal in hazard study. Vulnerability assessment, which is the other pillar of risk assessment, is not discussed here. With the current advance in hazard analysis, the traditional method for vulnerability assessment have become a bottleneck for risk assessment. Therefore, a vulnerability assessment method based on the debris flow action and building failure mechanism should be developed in our future works.

ACKNOWLEDGMENT:
This work has been supported by the grant from the Natural Science Foundation of China (4190084; 41030742) and Key Programs of the Chinese Academy of Sciences (Grant No. KZZD-EW-05-01)

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Received: 31 December, 2014
Accepted: 2 May, 2016