Response to Reviewer1 Comments

Manuscript title: (the original title: Hazard Assessment Comparison of Tazhiping Landslide Before and After Treatment)

Manuscript number: 2016-391

Thanks very much for reviewer's comments, which helped us to improve the quality of manuscript. We have made a major revision to address all the comments raised by the reviewer.

In the revised manuscript, all changes have been marked in RED which is suggested by the reviewers, and is modified by the authors.

We would be happy to make further modifications if required. We hope the changes listed have made the manuscript suitable for publication and we look forward to your response.

Q1: Some important questions remain still unanswered, namely the sensitivity of the friction parameters and more important the derivation of the best-fit parameters presented in Table 2. This aspect should be at least considered in the discussion and ideally in the methods section.

A1: It is very important the derivation of the best-fit calculated parameters .we have considered in the discussion and in the methods section. The present estimation of model parameters can be acquired by laboratory or small-scale experiments in some instance, however the Voellmy rheological model friction coefficient generally lacks a systematic approach to get. Therefore, we tested different coulomb friction coefficient μ values ranging between $0.1 \le \mu \le 0.6$ and viscous friction coefficient ζ values ranging between $100 \le \mu \le 1000 m \cdot s^{-2}$. Finally, we selected the coulomb friction coefficient $\mu = 0.45$ and viscous friction coefficient $\zeta = 500 m \cdot s^{-2}$ in accordance with back-analyses of well-documented landslide cases (Cepeda, J., et al. 2010; Du *et al.*, 2015). The text in the method section and discussion section have been revised. Please see p.12, line 267-274 and p.23, line 389-440.

Q2: The title does not promise detailed information about the numeric but rather a specification about the hazard assessment comparison. Therefore or the title or the content of the paper should be changed. The same is true for the abstract.

A2: This paper title has been revised to "Hazard Assessment Comparison of Tazhiping Landslide Before and After Treatment Using Finite Volume Method". The abstract has been revised. Please see p.1, line 2 and line 12-13.

Q3: There is some confusion in terminology for figures 6 and 7, that have to be changed. Figures should be improved. Figure 1 seems to be taken from an existing paper without citation.Figure 2 needs more information about the location of the study site in a global perspective and better visualization of the exact location in the Baisha river basin. figures 6 and 7 do not contain more details on the landslide area, location of the objects at risk, etc. This information is only given in figure 8 but visualized rather small. Readability of the outlines of buildings is very hard and not mentioned in the legend.

A3: The confusion in terminology for Figures.6 and 7 have been revised. Please see p.13,line 278; p.14,line 280; p.16,line 317 and p.17,line 319.

We have re-organized and added more information about the location of the studying site and Baisha river basin was shown in Figure 2. Please see p.9,line 212-214.

In Figures 6 and 7 we add more details on the landslide area shown in Figures 7a and 9a. Please see p.13,line 277-278.

Figure 10 has been extensively visualized and added the outlines of buildings in the legend. Please see p.21-22, line 367-373.

Various minor modification and revision were made in all Figures.

Q4: There are some publications in Chinese that are not accessible by all fellow scientist. There is some confusion for the article by Zhang,Z.Y., Wang,S.T., Wang,L.S.,et al., about the year of publication. In the text 1994 is mentioned while in the references there is written 1993. The reference of Toro, 1992 is missing.

A4: We have added all fellow scientist in the literature and revised all references according to the NHESSD journal style. We have cited the reference of Toro, 1992. Please see references section.

Other specific comments are given below.

Q5: p.2, line 61: what do the authors exactly mean with "landslide-debris flows?" Please rely on some definitions in the literature.

A5: There is some confusion about the mass movement process that is discussed and approached by the presented and adopted rheological model. On the one hand, Landslides move downslope in many different ways (Varnes, 1978). In addition flow-type landslides can evolve into rapidly travelling flows, which exhibit characteristics of debris flows on unchannelized or only weakly channelized hillslopes. The geomorphic heterogeneity of rapid shallow flow-type landslides such as hillslope debris flows is larger than observed in channelized debris flows, however many of these flows can be successfully modelled using the Voellmy-fluid friction relation and starting the flow as a block release (Christen et al., 2012). We have revised to flow-type landslides and given some definitions in the literature. Please see p2, line 63-64 and discussion section.

Q6: p.2, line 71: what to the autors exactly mean with 3D mapping of the division of hazard zones? Usually, hazards zonation is given on a map, e.g. in 2D

A6: It has been revised. Please see p.2, line 74.

Q7: p.3, line 98: this figure is taken from Christen et al., 2010. Please cite source.

A7: It has been added. Please see p.3, line 101.

Q8: p.3, line 107: missing space.

A8: It has been revised. Please see p.4, line 109.

Q9: p.7, line 178: this reference is missing in the reference section.

A9: It has been cited. Please see reference p.26, line 530-531.

" Toro, E.F.: Riemann problems and the waf method for solving the two dimensional shallow water equations, Philos. Trans. R. Soc. London, Ser., A 338, 43–68. 1992".

Q10: p.11, line 255: see comment for p.2, line 71

A10: It has been revised to 2D. Please see p.12, line 259.

Q11: p.11, line 266: figure is subtitled with "Thickness". Thickness of deposition is not equal to flow height (if a landslide really "flows"...). Please adapt wording.

A11: It has been revised to flow height. Please see p.1, line 15 ;see p.13, line 278 ; p14, line 287; p15, line 289; p.16, line 317; p17, line 327 and 328; p18, line 336; p23, line 411.

Q12: p.12, line 268: subtitle of figure is "Speed", legend says "Velocity". If the blue to green marked zone shows the deposited mass of the landslide, there should be no velocity value (because it's deposited). In chapter 3 is no indication or estimation about the speed of the landslide mass, therefore figure 6b does not really make sense.

A12: It has been revised to Velocity. Please see p.1, line 15 ;p.13, line 280; p15, line 290 and p.17, line 329.In any case, velocity plays a more important role regarding kinetic energy acting on an obstacle. However, the Miaoba residential area of Red Village is located at the frontal part of Tazhiping lanslide. Therefore, the maximum flow heigt of the landslide is one of the direct factors influencing the building's deformation failure status. Please see p.18, line 339-348 and p17, line 329.

Q13: p.12, line 270: not clear, if the colored area shows the maximum pressure or an instantaneous for a given time step. Much more of interest would be a local value (over time) at the position of a building. And why the legend goes up to more than 1000kPa but no reddih or yellowish areas are marked?

A13: The coloredbar shows the maximum values or an instantaneous pressure for a given time step. As the building of Red Village is located at the frontal part of landslide, the pressure of the middle and lower landslide deposits was about 200kPa. Thus, three-story and lower houses within the deposition range might be buried. The maximum pressure value in the surface gully in the middle and upper slope. According to field survey we have found this gully is in the elevation of about 1,200 m. The maximum pressure value is easy been found from the instantaneous for a given time step figures. Therefore, coupled with field observations and numerical simulation, they are especially helpful in understanding landslide movement process in complex terrain. It has been introduced in p.17, line 324-325.

Q14: p.12, lines 274, 277 and p.13, line 278: not clear what numbers in the circle mean. Is this kind of a list or does it indicate a location in a figure?

A14: No, it does not indicate a location. It has been deleted. Please see p.18, line 339-348.

Q15: p.13, line 279: how is made this separation between houses of different numbers of stories? Please give more information and references to it.

A15: The building is 3m height each floor in China. We have cited some literatures (Hungr et al., 1984; Petrazzuoli et al., 2004; GB, 50010–2010; Hu et al., 2012; Zeng et al., 2015). Please see p18, line 358 and 359.

Q16: p.13, line 293: or indicate "about 1.2 m" or give exact value.

A16: The more exact value has been given . " with an elevation of 1,070-1,072m and a length of 182m." Please see p.15, line 312-313.

Q17: p.13, line 298: same remark as for figure 6a.

A17: It has been revised. Please see A.11.

Q18: p. 14, line 300: same remark as for figure 6b

A18: It has been revised. Please see A.12.

Q19: p.14, line 305: example of a sentence that has to be rewritten because of wrong word order

A19: We have revised to "Provided in Fig.7 are the kinematic characteristics of the landslide deposit." Please see p.17, line 324.

Q20: p.14, lines 305, 308, 309: not clear what numbers in the circle mean.

A20: It has been deleted. Please see p.17, line 325-330.

Q21: p.15, line 321/322: not sure, if this statement is really true. There may be examples where entire houses on a landslide mass are moved but not destroyed because of stable base plates. In any case, velocity plays a more important role regarding kinetic energy acting on an obstacle. You are right in the sense that the height of a moving landslide (e.g. the frontal part) plays an important role when it hits a building on a higher level, e.g. the second or third floor. Please clarify this point.

A21: We have clarified this point. "Landslides reflect landscape instability that evolves over meteorological and geological timescales, and they also pose threats to people, property, and the environment. The severity of these threats depends largely on landslide speed and travel distance. There may be examples where entire houses on a landslide mass are moved but not destroyed because of stable base plates. In any case, velocity plays a more important role regarding kinetic energy acting on an obstacle. However, the Miaoba residential area of Red Village is located at the frontal part of Tazhiping lanslide." Please see p.18,lines 341-348.

Q22: p.15, 16 and 17, table 3: the term "washed away" is not suitable for landslide process. It implies an major influence by a fluid.

A22: It has been revised. Please see p.18,lines 361.

Q23: p.17, line 333: This should be 2D, because you show a map with the different zonations. These different zonations are not defined, by the way.

A23: It has been revised to 2D. Please see p.20, line 362 and p.22,line 375.

Q24: p.17, line 339: There seem to be marked buildings (in the red high-hazard zone). If so, adjust legend and make sure they are better visible. What zone is defined outside the colored area? No hazard or also low-hazard zone?

A24: We have adjusted legend and defined outside the colored area as no-hazard. Please see p.20, line 366-368 and Figure.10 legend.

Q25: p.18, line 342: same as for figure 8a. And this should be 8b instead of 8c

A25: It has been revised. Please see p.22, line 374.

Q26: p.18, line 350: what is a landslide-debris flow?

A26: It has been defined. Please see p.23, line 410 and answer A5.

Q27: p.18, line 358: this should be 2D

A27: It has been revised. Please see p.23, line 418.

Q28: p.19, line 411: correct reference would be: Michael-Leiba, M., Baynes, F., Scott, G., Granger, K. 2003. Regional landslide risk to the Cairns community [J]. NatHazards, 2003,30 (2):233–249. Check reference style for all references according to the journal style!

A28: We have revised all references according to the NHESSD journal style. The reference list has been updated as well. Please see references section.

The text of the manuscript has been revised.

Response to Reviewer2 Comments

Manuscript title: (the original title: Hazard Assessment Comparison of Tazhiping Landslide Before and After Treatment)

Manuscript number: 2019-391

Thanks very much for reviewer's comments, which helped us to improve the quality of manuscript. We have made a major revision to address all the comments raised by the reviewer.

In the revised manuscript, all changes have been marked in RED which is suggested by the reviewers, and is modified by the authors.

We would be happy to make further modifications if required. We hope the changes listed have made the manuscript suitable for publication and we look forward to your response.

Q1: The main contribution of this paper seems to be the computational model proposed. It is desired to add related descriptions to the title of this paper.

A1: This paper title has been revised to "Hazard Assessment Comparison of Tazhiping Landslide Before and After Treatment Using Finite Volume Method". Please see p.1, line 2.

Q2: Previous study on landslide/debris flow issues using the fluid mechanics based method had faced the problem that it predicts higher mobility of the moving body while using the same fluid parameters throughout the whole flowing process. For example, less obvious fluid property is expected when the flow body is approaching stop point. It is stated in this manuscript that a changed frictional resistance is used (L78). However, the details are not clear in the text. Relevant descriptions on this issue should be strengthened.

A2: This paper adopted the RAMMS to simulate the mass movement process. In RAMMS, we can automatically generate the friction coefficient for our calculation domain based on topographic data analysis, forest information and global parameters and so on. Therefore, we can used a changed frictional resistance. This problem has considered in the discussion section. Please see p.22-23, line 378~406.

Q3: It is not clear in the text that how the free surface of the landslide/debris flow is treated or reconstructed. An additional figure is need to describe the details.

A3: We have reconstructed and added Figure4. Please see p.10, line 218.

Q4: Fig.4 showed the geological profile of Taziping Landslide and a slide surface is clearly indicated. Is this slide surface comparable with the simulation result? It would be interesting to show their comparison.

A4: We have reconstructed and added Figure8. Before engineering treatment, Figure.4 and Figure.5 have showed that the sliding mass had an estimated starting volume of about 600,000m^3 and a mean thickness of 8m. After fully accounting for the slide-resistant piles and mounds, we introduced the Morgenstern-Price method to calculate the stability coefficient of Taziping landslide after treatment. The method was determined with an iterative approaching by changing the position of the sliding surface until failure of the dumpsite (Figure.8). Please see p.15, line 300~302 and 306~308.

Q5: In Tab.3, Various hazard zone levels were cataloged. What is the criterial to assign a specific damage situation to a certain zone level? Is there any standard code to follow?

A5: We have cited standard code and literature(Fell R et al., 2008; Qiao , 2009; DZ/T 0286-2015). Please see p.18, line 354~355.

Other specific comments are given below.

Q6: The quotations in the manuscript are not in the same format, for example, Line 44, Costa, 1984; VS Line 50, Zhang. Y, 2013. Usually only family name is preferred, please refer to the journal's instructions and make necessary changes throughout the text. p.11, line 266: figure is subtitled with

A6: It has been revised. We have revised all references and quotations in the manuscript according to the NHESSD journal style. The reference list has been updated as well. Please see references and quotations section.

Q7: Fig.1 needs proper citation.

A7: It has been revised (Christen et al., 2010a).

Q8: In Fig.6, Fig.7, what moment of flow does these figures represent? Different moment should have different deposit thickness, flow velocity and pressure. Please confirm.

A8: The Figure.6 and Figure.7 is shown that the last moment of the flow. Different moment have different deposit flow height, velocity and pressure. However, the coloredbar shows the maximum values or an instantaneous for a given time step. It has been revised. Please see p.17, line 324-325.

Q9: L276 "The middle and lower deposits had a thickness of about 5-10m", confusing here, what does "the middle and lower deposits" mean? Similar as "the middle and lower movement speed", please check throughout the text.

A9: This sentences has been reformulated, because of wrong word order. Please see p.14, line 288 and p.17, line 328.

Q10: L289. What technique is used for searching the sliding plane.

A10: Coupled with field borehole surveying and numerical calculation method to search the sliding plane.

Q11: L305, Fig.4 should be Fig.7.

A11: It has been revised. Please see p.17, line 324. Please see p18, line 358 and 359.

Q12: Tab.3. How is the "Building damage probability" evaluated?.

A12: By the thickness of the landslide mass to evaluate the ability of a building to withstand a landslide disaster. I have cited some literatures (Hungr et al., 1984; Petrazzuoli et al., 2004; GB, 50010–2010; Hu et al., 2012; Zeng et al., 2015). Please see p18, line 358 and 359.

The text of the manuscript has been revised.

Hazard Assessment Comparison of Tazhiping Landslide Before and After Treatment using finite volume method

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Abstract: Through investigation and analysis of geological conditions and mechanical parameters of the Taziping landslide, the finite volume method was adopted, and, the rheological model was adopted to simulate the landslide and avalanche entire mass movement process. The present paper adopted the numerical approach in RAMMS and the GIS platform to simulate the mass movement process before and after treatment. This paper also provided the conditions and characteristic parameters of soil deposits (~~thickness~~ flow height, ~~speed~~ velocity, and stresses) during the landslide mass movement process and mapped the 3D division of hazard zones before and after landslide treatment. Results indicated that the scope of hazard zones contracted after engineering treatment of the landslide. The extent of high-hazard zones was reduced by about 2/3 of the area before treatment, and characteristic parameters of the mass movement process after treatment decreased to 1/3 of those before treatment. Despite engineering treatment, the Taziping landslide still poses significant hazard to nearby settlements. Therefore, we propose that houses located in high-hazard zones be relocated or reinforced for protection.

Keywords: finite volume method; rheological model; motion feature parameters; hazard assessment

1. Introduction

The hazards of a landslide include scope of influence (i.e., source area, possible path area, and backward and lateral expansion area) and secondary disasters (i.e., reservoir surge, blast, and landslide-induced barrier lake). A typical landslide hazard assessment aims to propose a systematic hazard assessment method with regard to a given position or a potential landslide. Current research on typical landslide hazard assessment remains immature, and there are multiple methods for interpreting landslide hazards. To be specific, the scope of influence prediction of a landslide refers to deformation and instability characteristics such as sliding distance, movement speed, and bulking thickness range. The movement behavior of a landslide mass is related to its occurrence, sliding mechanisms, mass characteristics, sliding path, and many other factors. Current landslide movement prediction methods include empirical prediction and numerical simulation.

Empirical prediction method: The empirical prediction method involves analyzing landslide flow through the collection of landslide parameters in the field. It further consists of the geomorphologic method (Costa, 1984; Jackson et al., 1987; Scott et al., 1993), the geometric change method (~~Zhang et al., 1994 1993;~~ Finlay et al., 1999; Michael-Leiba et al., 2003), and the volume change method (Fannin et al., 2001). Empirical models are commonly simple and easy to apply, and the required data are easy to obtain as well. **Numerical simulation method:** Numerical simulation methods are further divided into the continuous deformation analysis method (Hungr, 1995; Evans et al., 2009; ~~Zhang .Y, 2013~~; Wang~~. L~~, et al., 2016), the discontinuous deformation analysis method (Shi~~.G.H~~, 1988; ~~Yin et al., 2002~~), and the simplified analytical simulation method (Christen et al., 2010a; Sassa, 2010; Bartelt et al., 2012; Du et al., 2015). The numerical simulation method expresses continuous physical variables using the original spatial and temporal coordinates with geometric values of discrete points. Numerical simulations follow certain rules to establish an algebraic equation set in order to obtain approximate solutions for physical variables.

Empirical prediction models only provide a simple prediction of the sliding path. Due to the differences in geological environments, empirical prediction models commonly have low generality. The continuous deformation method has the advantage of an extremely strong replication capability, but it is not recommended when analyzing flow-type landslides~~-debris flows~~, lahars, or debris flows because of complicated rheological behaviors (Iverson et al., 1997, 2001; Hungr et al., 2001; Portilla et al., 2010;Chen et al., 2014). The fluid mechanics-based discontinuous deformation method has several shortcomings such as, great computational burden, difficult parameter selection, and difficult 3D implementation. The simplified analytical simulation method fully takes into account the flow state properties of landslides before introducing a rheological model and can easily realize 3D implementation on the GIS platform. On that account, this paper adopted the continuous fluid mechanics-based finite volume method (simplified analytical simulation method). We introduce a rheological model on the basis of using mass as well as momentum and energy conservation to describe the movement of landslides. We also employed GIS analysis to simulate the entire movement process of Taziping landslide and map the 2D division of hazard zones.

2. Methods

2.1 Kinetic analysis method

Adopting the continuous fluid mechanics-based finite volume method, this paper took into account erosion action on the lower surface of the sliding mass and the change in frictional resistance within the landslide-debris flow in order to establish a computational model. The basic idea is to divide the calculation area into a series of non-repetitive control volumes, ensuring that there is a control volume around each grid point. Each control volume is then integrated by the unresolved differential equation in order to obtain a set of discrete equations. The unknown variable is the numerical value of the dependent variable at each grid point. To solve the integral of a control volume, we make a hypothesis about the change rule of values among grid points, that is, about their piecewise distribution profile. The finite volume method can satisfactorily overcome the finite element method's weakness of slow calculation, and solve the problem of complex region processing. Thus, we adopted the finite volume method to establish the kinematic model for the landslide flow process.

The core of the finite volume method is domain discretization. The finite volume method uses discrete points as a substitute for continuous space. The physical meaning of the discrete equation is the conservation of the dependent variable in a finite control volume. Establishment of the conservation equation is based on the continuous movement model, that is, the continuity hypothesis about landslide substances. We divided the landslide mass into a series of units and made the hypothesis that each unit has consistent kinematic parameters (speed at a depth, density, etc.) and physical parameters (Fig.1). We also established an Eulerian coordinate system-based conservation equation with regard to each control volume.

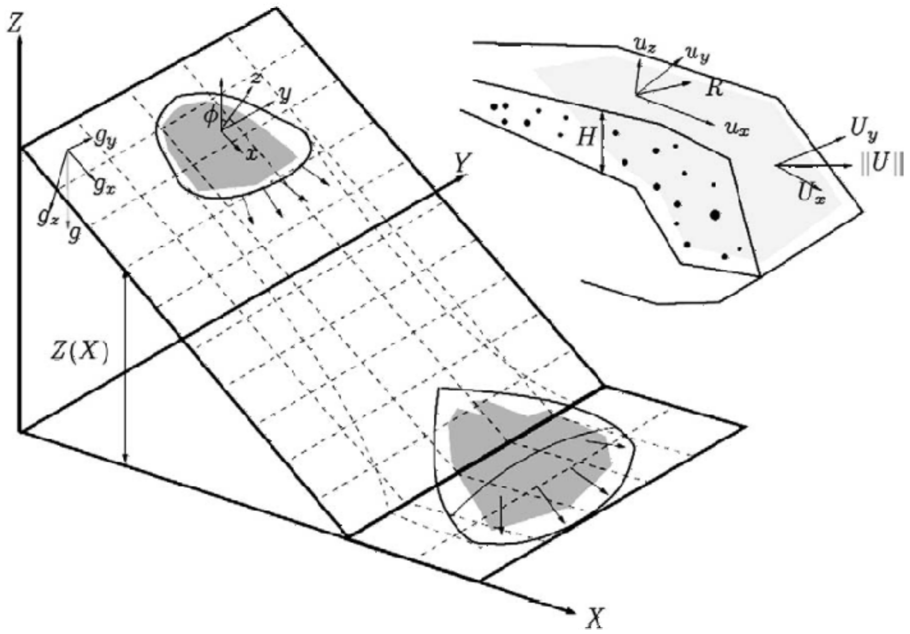


Fig.1 Schematic diagram of finite volume discretization (Christen et al., 2010a).

2.2 Control equation

The computational domain is defined as directions x and y, and the topographic elevation is given the coordinate $z(x,y)$. $H(x,y,t)$ is assumed as the change relationship of landslide thickness with time; $U_x(x,y,t)$ and $U_y(x,y,t)$ respectively represent the mean movement speeds along directions x and y at moment t; $n_x = U_x \big/ \sqrt{U_x^2 + U_y^2}$ and $n_y = U_y \big/ \sqrt{U_x^2 + U_y^2}$ represent the cosinoidal and sinusoidal flow vectors of the landslide on the plane x - y. The mean flow speed of substances is defined as $U=\sqrt{U_x^2+U_y^2}$.

Thus, the mass balance equation becomes:

$$\partial_t H+\partial_x(HU_x)+\partial_y(HU_y)=\dot{Q} \tag{1}$$

wherein, $\dot{Q}(x,y,t)$ represents the change rate (entrainment rate) of landslide volume with time.

Assuming that $l(x,y,t)$ represents the movement distance of the landslide with time, we can obtain:

$$\dot{Q}=\begin{cases} 0 & if \quad h_i=0 \\ \dfrac{\rho_i}{\rho_a}h_i\dfrac{U}{l} & if \quad k_i l\geq h_i \\ \dfrac{\rho_i}{\rho_a}k_i U & if \quad k_i l<h_i \end{cases} \tag{2}$$

wherein, h_i represents the thickness of the ith layer of the landslide in the movement process; ρ_i represents the density of the ith layer of the landslide in the movement process; ρ_a represents the density of the landslide; the dimensionless parameter k_i represents the entrainment rate.

The momentum balance equation is:

$$\partial_t\left(HU_x\right)+\partial_x(HU_x^2+\frac{g_z k_{a/p}H^2}{2})+\partial_y(HU_xU_y)=S_{gy}-S_f(R)\left[n_x\right] \tag{3}$$

$$\partial_t\left(HU_y\right)+\partial_y(HU_y^2+\frac{g_z k_{a/p}H^2}{2})+\partial_x(HU_xU_y)=S_{gx}-S_f(R)\left[n_y\right] \tag{4}$$

wherein, $S_{gx}=g_xH$ and $S_{gy}=g_yH$ represent the dynamic components of the acceleration of gravity in directions x and y; $g=(g_x \quad g_y \quad g_z)$ represents the vector of the acceleration of gravity; $k_{a/p}$ represents the pressure coefficient of soil; ρ_a represents the density of the landslide; the dimensionless parameter k_i represents the entrainment rate; $S_f(R)$ represents the frictional resistance.

The kinetic energy balance equation is:

$$\partial_t(HR)+\partial_x(HRU_x)+\partial_y(HRU_y)=\dot{P}-\dot{D} \tag{5}$$

wherein, $R(x,y,t)$ represents the random mean kinetic energy of the landslide; $\dot{P}(x,y,t)$ and $\dot{D}(x,y,t)$ represent the random increased kinetic energy and decreased kinetic energy of the landslide.

2.3 Constitutive relationship

The improved Voellmy rheological model is applied in the computational simulation of the landslide. See the computational formula below:

$$S_f = \frac{u_i}{\|U\|}\left(h\mu g_z + R_t U^2 + R_\zeta U^2\right) \tag{6}$$

$$R_t = \mu h \frac{U^T K U}{U^2}, R_\zeta = \frac{g}{\zeta} \tag{7}$$

wherein, $u_i/\|U\|$ represents the unit vector in the movement direction of the landslide; μ represents the Coulomb friction coefficient, and is related to $R(x,y,t)$, the random mean kinetic energy of the landslide; R_t represents the gravity-related frictional force coefficient; K represents the substrate surface curvature; ζ represents the viscous friction coefficient of the "turbulent flow".

2.4 HLLE-Heun numerical solution

Synthesizing control equations (1), (3), (4) and (5), we can obtain the simplified form of the nonlinear hyperbola equation:

$$\partial_t V + \nabla \cdot F(V) = G(V) \tag{8}$$

$$V = \begin{pmatrix} H \\ HU_x \\ HU_y \\ HR \end{pmatrix} \qquad G(V) := \begin{pmatrix} \dot{Q} \\ S_{gx} - S_{fx} \\ S_{gy} - S_{fy} \\ \dot{P} - \dot{D} \end{pmatrix}$$

$$F(V) = \begin{pmatrix} HU_x & HU_y \\ HU_x^2 + g_z k_{a/p}\frac{H^2}{2} & HU_xU_y \\ HU_xU_y & HU_y^2 + g_z k_{a/p}\frac{H^2}{2} \\ HRU_x & HRU_y \end{pmatrix}$$

wherein, $V(x,y,t)$ represents a vector equation consisting of four unknown vector variables; $F(V)$ represents the flux function; $G(V)$ represents the source term. Based on the HLLE equation of the finite volume method and the quadrilateral grid, the node layout can adopt the grid center pattern, and the normal flux along one side of the control volume can be represented by the flux at the center of the side. The finite volume discretization adopting the control volume as unit is depicted in Fig.1; the Gauss theorem can be followed for the integration of equation (8), wherein C_i represents the unit volume; after converting the volume integral flux function $F(V)$ into the curved surface integral, we can obtain:

$$\int_{C_i} \partial_t V dx + \oint_{\partial C_i} F(V) \cdot n_i d\sigma = \int_{C_i} G(V) dx \tag{9}$$

wherein, n_i represents the outward normal direction vertical to unit C_i at the boundary; through adopting the HLL format for the discretization of surface integral, the following simplified form can be obtained:

$$V_i^{(*)} = V_i^{(n)} + \frac{\Delta t}{A_{C_i}} \Delta F_i^{(HLL)}\left(V^{(n)}\right) \tag{10}$$

$$V_i^{(**)} = V_i^{(*)} + \frac{\Delta t}{A_{C_i}} \Delta F_i^{(HLL)}\left(V^{(*)}\right) \tag{11}$$

$$V_i^{(n+1)} = \frac{1}{2}\left(V_i^{(n)} + V_i^{(**)}\right) \tag{12}$$

wherein, $V_i^{(n)}$ represents the mean value of unit variables at moment $t^{(n)}$; $V^{(n)}$ represents the mean value of the entire grid at moment $t^{(n)}$; $\Delta t := t^{(n-1)} - t^{(n)}$ represents the calculated time step; A_{C_i} represents the area of unit C_i; $\Delta F_i^{(HLL)}$ represents the approximate value of the curved surface integral, as shown below:

$$\Delta F_i^{(HLL)}\left(V^{(n)}\right) := -\sum_{j=1}^{4} F_{ij}^{(HLL)}\left(V^{(n)}\right) n_{ij} \Delta X \tag{13}$$

wherein, n_{ij} represents the outward normal direction of the i th unit at boundary j; the flux calculation term $F_{ij}^{(HLL)}\left(V^{(n)}\right)$ represents the approximate solution mode of the Riemann problem of the i th unit at boundary j; see the computational formula below:

$$F_{ij}^{(HLL)}\left(V^{(n)}\right) = \begin{cases} F\left(V_L^{(n)}\right) & 0 \le S_L \\ \dfrac{S_R F\left(V_L^{(n)}\right) - S_L F\left(V_R^{(n)}\right) + S_R S_L F\left(V_R^{(n)} - V_L^{(n)}\right)}{S_R - S_L} & S_L \le 0 \le S_R \\ F\left(V_R^{(n)}\right) & S_R \le 0 \end{cases} \tag{14}$$

wherein, $V_L^{(n)}$ and $V_R^{(n)}$ respectively represent the approximate values of $V^{(n)}$

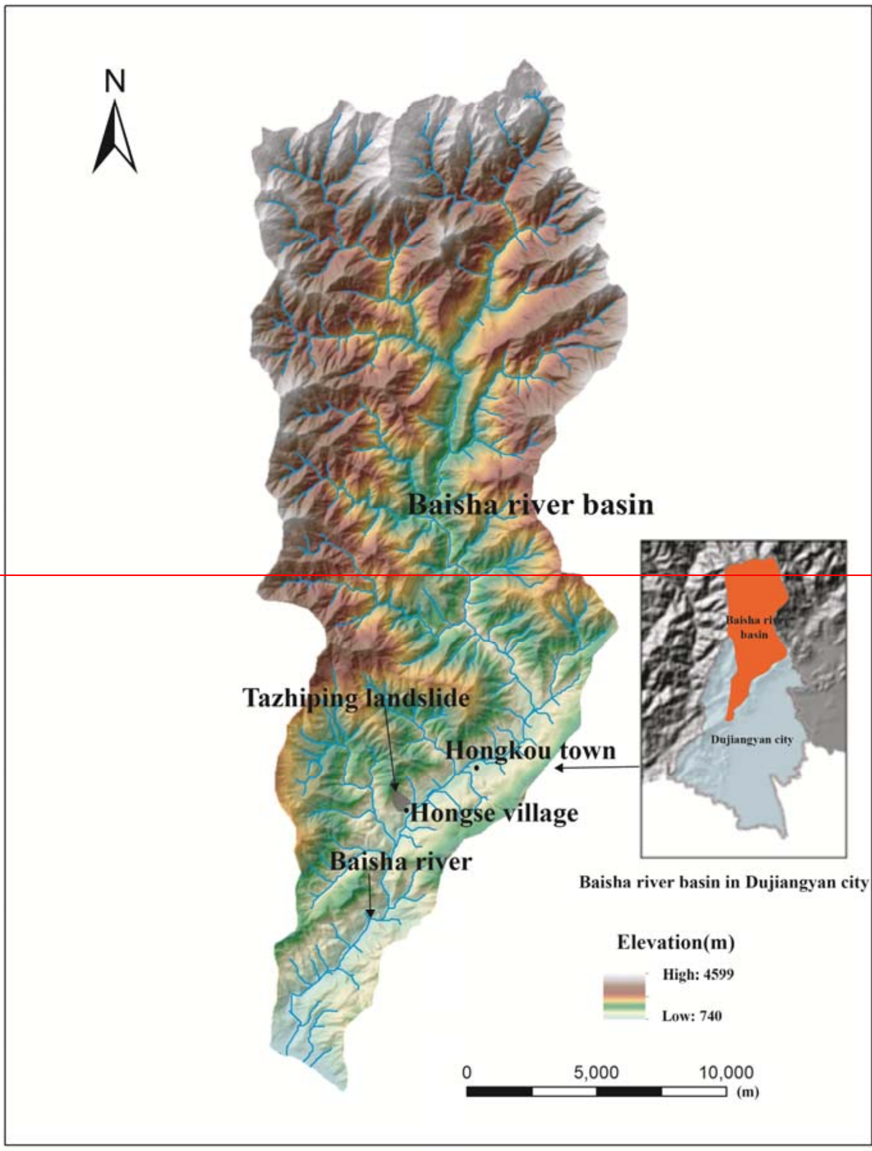
on both sides of boundary j of the ith unit; S_L and S_R respectively represent the wave speeds on the left and right sides. Refer to the computational method described by Toro (1992). In addition, the gradient magnitude in the original second-order difference equation can be limited through multiplication with the flux limiter, and the second-order format of the TVD property can be constructed to avoid the occurrence of numerical oscillation. Refer to the specific method described by LeVeque (2002).

In this paper numerical solver used within RAMMS, which was specifically designed to provide landslide(avalanche) engineers with a tool that can be applied to analyze problems that two-dimensional depth-averaged mass and momentum equations on three-dimensional terrain using both first and second-order finite volume methods (Christen et al., 2010b).

3. Study area and data

3.1 Taziping landslide

Taziping landslide is located in the southeast of the Hongse Village, Hongkou Town, Dujiangyan City of Sichuan Province. The site is located at (E103°37′46″, N31°6′29″), 68 km away from Chengdu City to the east and 20 km away from the Dujiangyan Urban District (Fig. 2). Its geomorphic unit is a middle-mountain tectonic erosion area, falling within the slope geomorphology on the right bank of the Baisha River Valley. As an colluvial layer landslide triggered by the Wenchuan Earthquake, Taziping Landslide is a large-scale landslide as shown in Fig. 3. It has a gradient of 25°-40° with an average of about 32°. The landslide has an apparent round-backed armchair contour, and has formed a steep rear edge, which has a gradient of 35°-50° and an elevation of about 1,370 m. The front edge is located on the south side of the mountain road, and has an elevation of about 1,007 m. The landslide has an elevation difference of about 363 m, and the main sliding direction of 124°NE. The landslide mass is in an irregular semi-elliptical shape, and has a length of about 530 m, an average width of 145 m and a landslide area of approximately 7.68×10^4 m^2. The landslide mass is gravelly soil in lithology, and is covered on the surface by silty clay mingled with gravels. In terms of spatial distribution, it is thick in the middle and thin on the lateral edges, and has a thickness of 20-25 m and a volume of approximately 1.16×10^6 m^3. During the earthquake, the landslide mass slid to cover the northern mountain slope mass of the Hongse Village Miaoba settlement. The landslide has an apparent front edge boundary, and there is also a swelling deformation (Fig. 4).

211 
N
Baisha river basin
Baisha river basin
Dujiangyan city
Tazhiping landslide
Hongkou town
Hongse village
Baisha river
Baisha river basin in Dujiangyan city
Elevation(m)
High: 4599
Low: 740
0
5,000
10,000
(m)

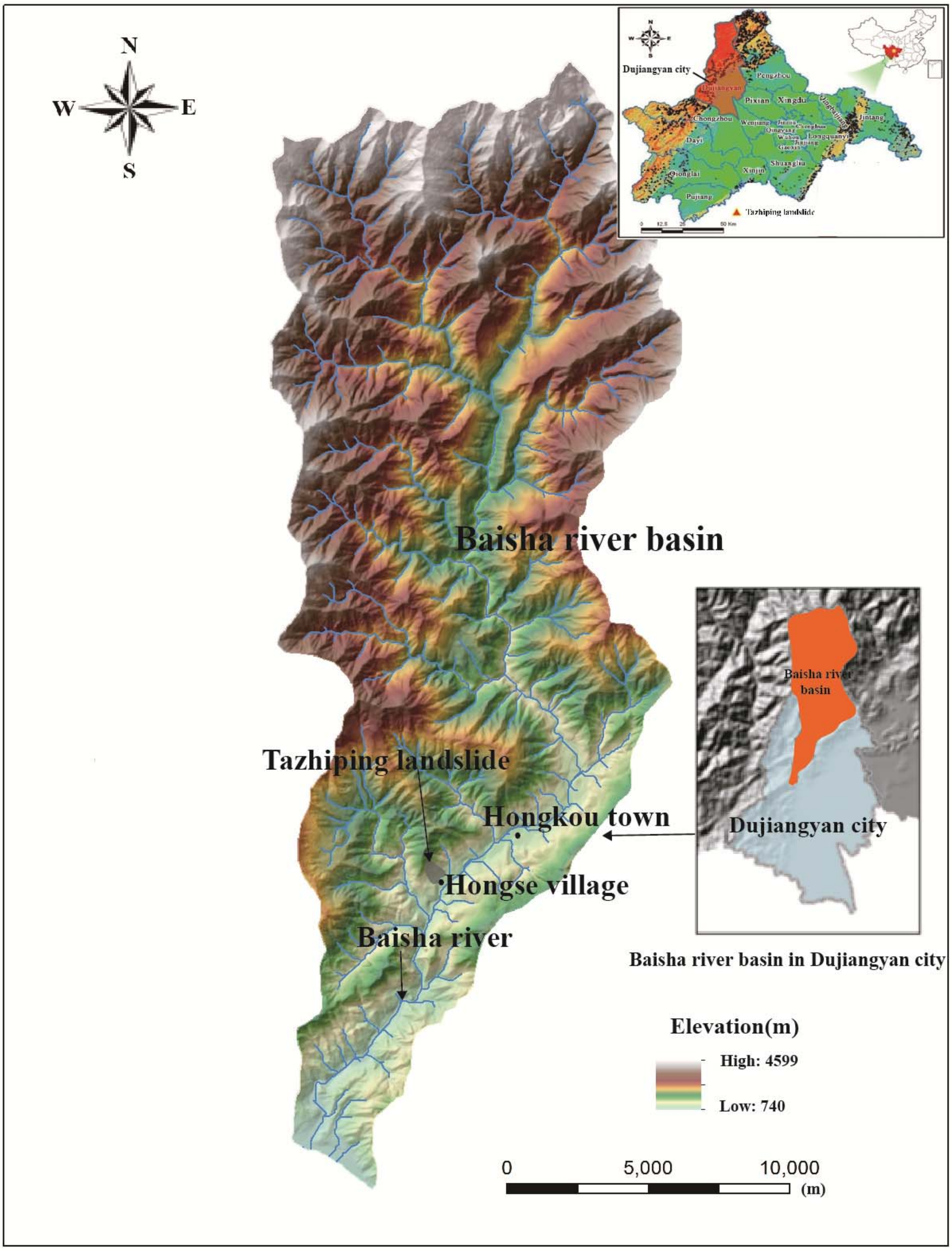


Fig.2 Location of Tazhiping landslide, Baisha river basin, Dujiangyan city (the landslide triggered by Wenchuan Ms 8.0 earthquake on May 12, 2008)

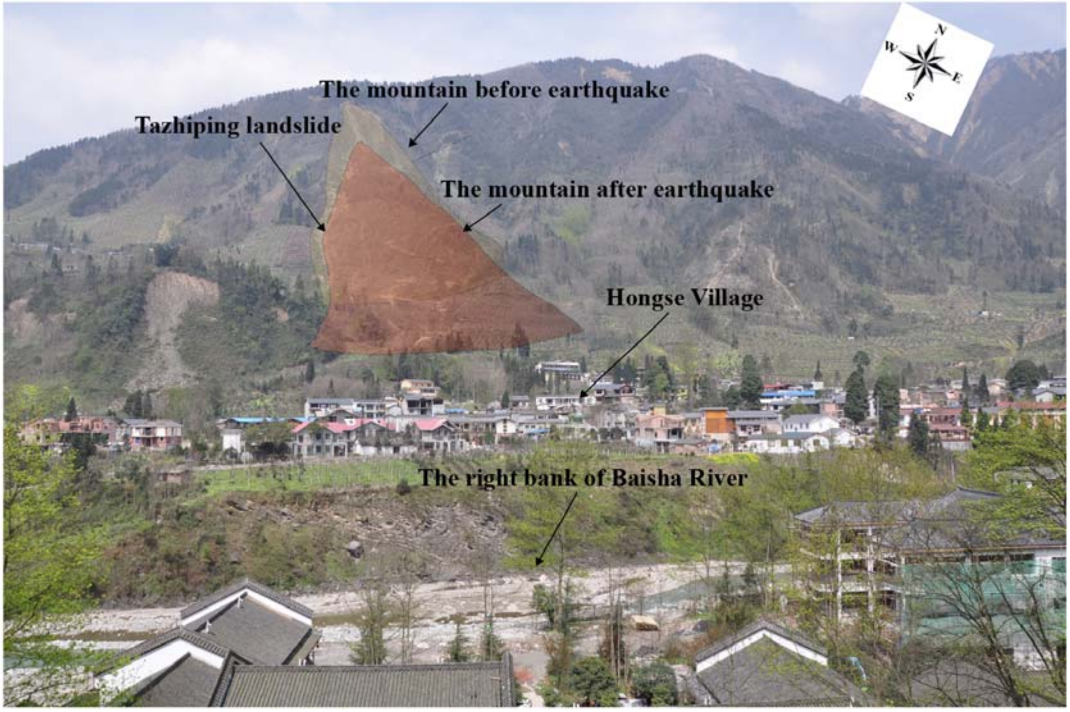


Fig.3 Taziping Landslide

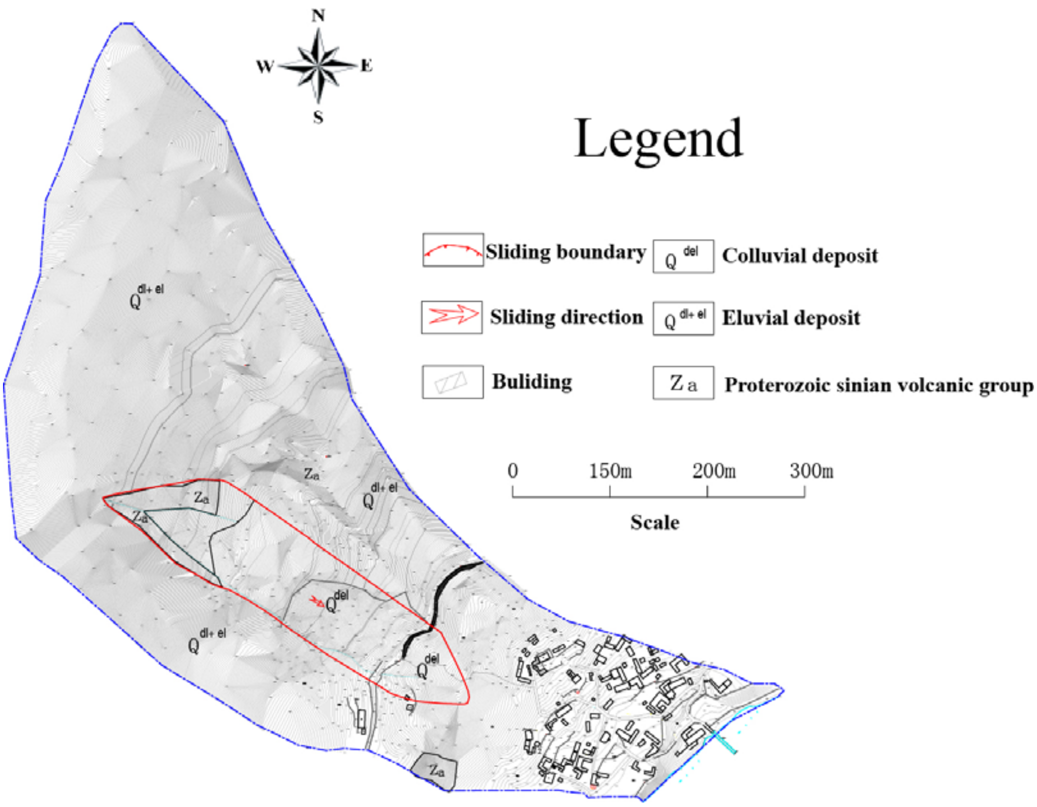


Fig.4 Plane sketch of Tazhiping landslide

After Wenchuan Earthquake, the massive colluvial deposits covers on the mountain slope, and the landslide mass is dominated by the colluvium. The colluvium is mainly distributed on the top surface of the landslide mass in the thickness of

0.5-5.0 m, and is mainly constituted by rubbles and gravels. The mass consists of a small amount of fine gravel substances which are gray or grayish-green, and dominated by andesite in composition, generally with a block size of 20-150 cm. Field survey indicates that the rubbles in the surface layer have a maximum diameter exceeding 2 m, and that fine gravel substances are filled among rubbles in a loose structure. Within the thickness of 5-10 m, the landslide mass is constituted of a small amount of yellowish-brown and gray-brown silty clay mingled with 5-40% of non-uniformly distributed broken rubbles. Within the thickness of 10-25 m, there is a wide distribution of gravelly soil. The soil is grayish-green or variegated in color, is slightly compact and non-uniform, and has a broken stone content of about 50%. The parent rock of the broken stones is andesite, filled with silty clay or silt (Fig.4 5). Table 1 shows the parameters of the surface gravelly soil of the landslide mass based on the field sampling.

Tab.1 Parameters of the surface soil of Taziping Landslide

Internal friction angle (°)		**Cohesion (kPa)**	**Relative compactness**	**Natural void ratio**	**Dry density ($kN·m^{-3}$)**	**Specific gravity ($g·cm^{-3}$)**
Peak	**Residual**					
27.5	23	20.5	53%	0.789	15.357	2.492

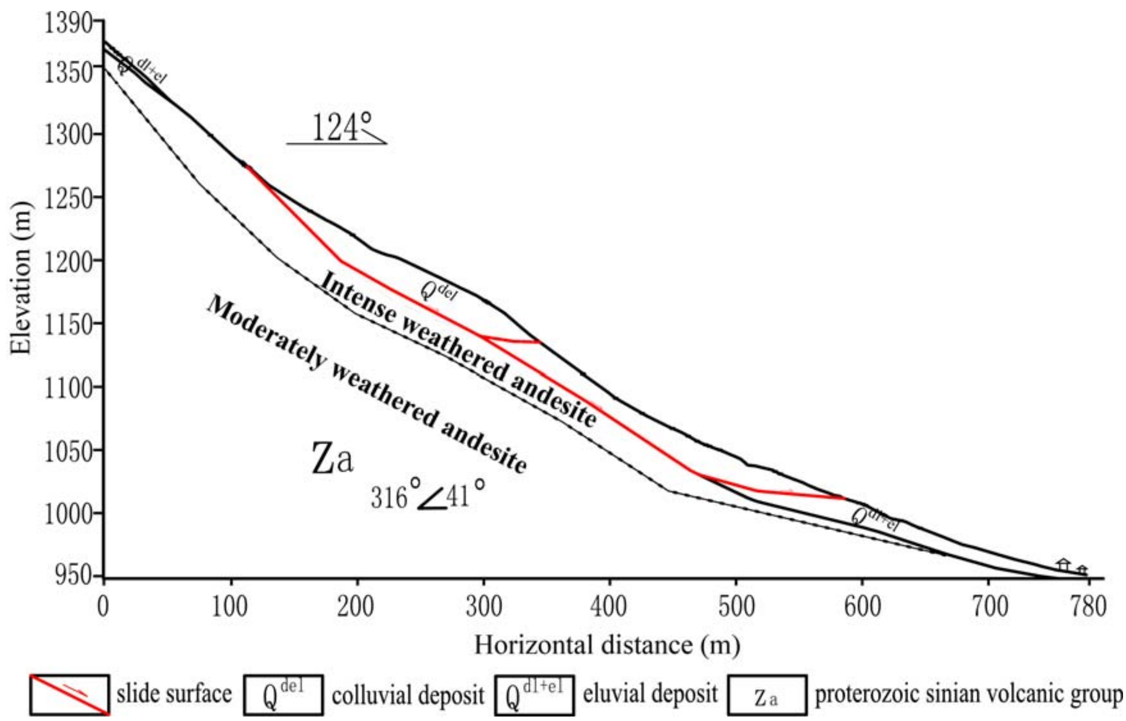


Fig.4 5 Geological profile of Taziping Landslide

The landslide is an unconsolidated mass containing relatively large amounts of crushed stones and silty clay (Fig.5 6). Its loose structure and strong permeability facilitate infiltration of surface water. The Wenchuan earthquake aggravated the deformation of the landslide making deposits more unconsolidated, further reducing the stability of the landslide mass. During persistent rainfall, surface water infiltrates the landslide slope resulting in increased water pressure within the landslide mass and reduced shear strength on the sliding surface. Thus, rainfall constitutes the primary inducing factor of the upper Taziping landslide. After infiltrating the loose layer, water saturates the slope increasing the dead weight of the sliding mass and reducing the shear strength of soil in the sliding zone. Infiltration into the landslide mass also increases the infiltration pressure of perched water, drives deformation, and poses a great threat to villages located at the front of the landslide. Slide-resistant piles and backfill were place at the toe of the slope in order to reduce the hazards of future slides. The slide-resistant piles have enhanced the overall stability of the slope, however, under heavy rainfall the upper unconsolidated landslide deposits may cut out from the top of the slide-resistant piles.

(a) Material on the landslide surface (b) Material in the shear zone

Fig.~~5~~ 6 Colluvial deposits covers on the mountain slope

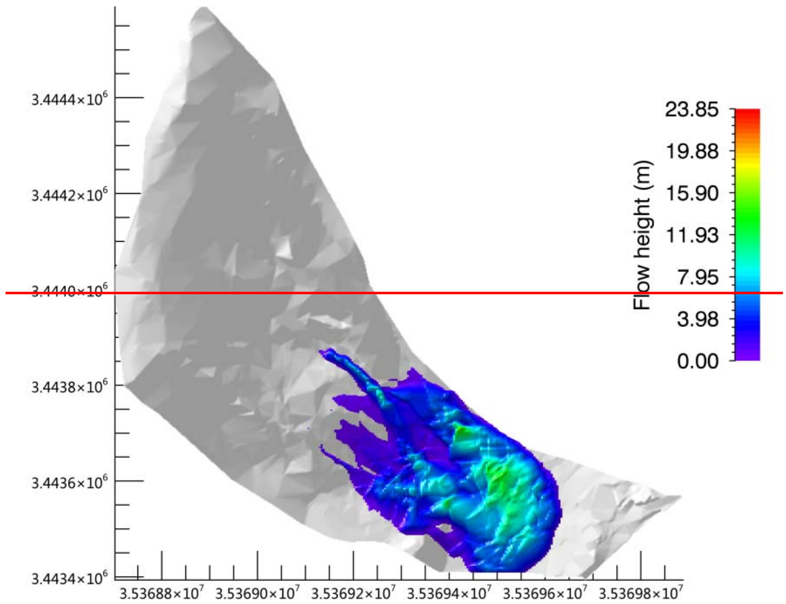
Therefore we simulate possible movement states of the Taziping landslide before and after treatment with slide-resistant piles, comparatively analyzed the kinetic parameters in the movement process, and mapped the ~~3~~2D division of hazard zones.

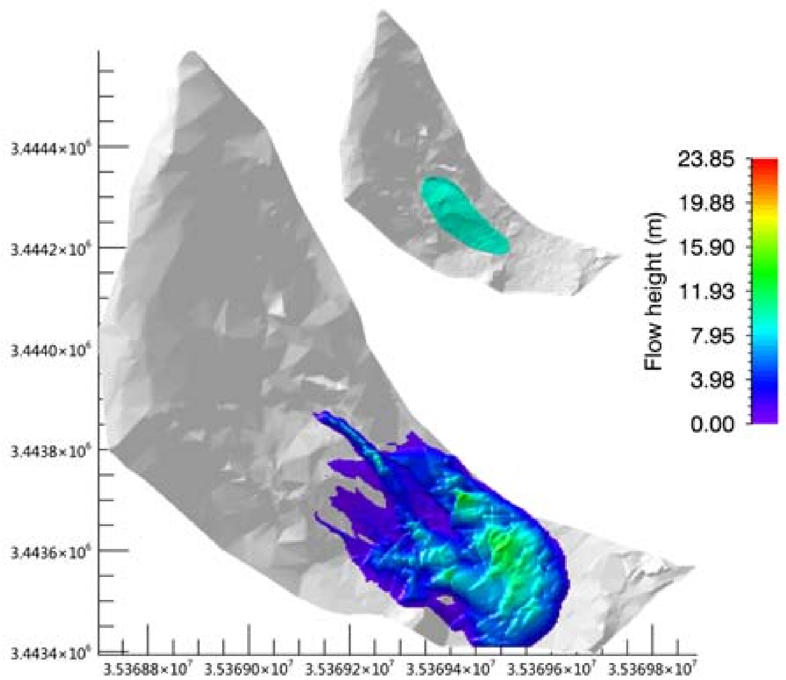
3.2 Hazard prediction before treatment

It was assumed that the landslide was damaged before engineering treatment. According to field investigation, the sliding mass had an estimated starting volume of about 600,000m^3 and a mean thickness of 8m. Based on the survey report and field investigation (Hydrologic Engineering and Geological Survey Institute of Hebei Province, 2010), we adopted the survey parameters of Tab.2 for the simulated calculation. These parameters obtained from performing laboratory or small-scale experiments and back-analyses of relatively well-documented landslide cases. The unit weigh $\gamma = 20.8kN \cdot m^{-3}$ which we used is from small-scale conventional triaxial test experiments in laboratory. In addition, we selected the coulomb friction coefficient $\mu = 0.45$ and viscous friction coefficient $\zeta = 500m \cdot s^{-2}$ in accordance with back-analyses of well-documented landslide cases (Cepeda et al., 2010; Du et al., 2015). The erosional entrainment rate selected the minimum value $k_i = 0.0001$ in program RAMMS.

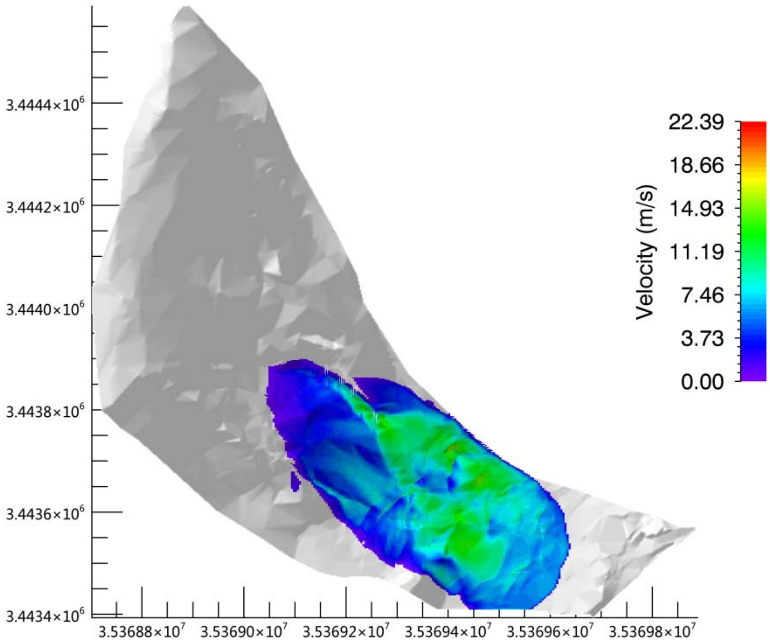
Tab.2 Model calculation parameters

Unit weight $\gamma(kN\cdot m^{-3})$	**Coulomb friction coefficient** μ	**Viscous friction coefficient** $\zeta(m\cdot s^{-2})$	**Erosional entrainment rate** k_i
20.8	0.45	500	0.0001

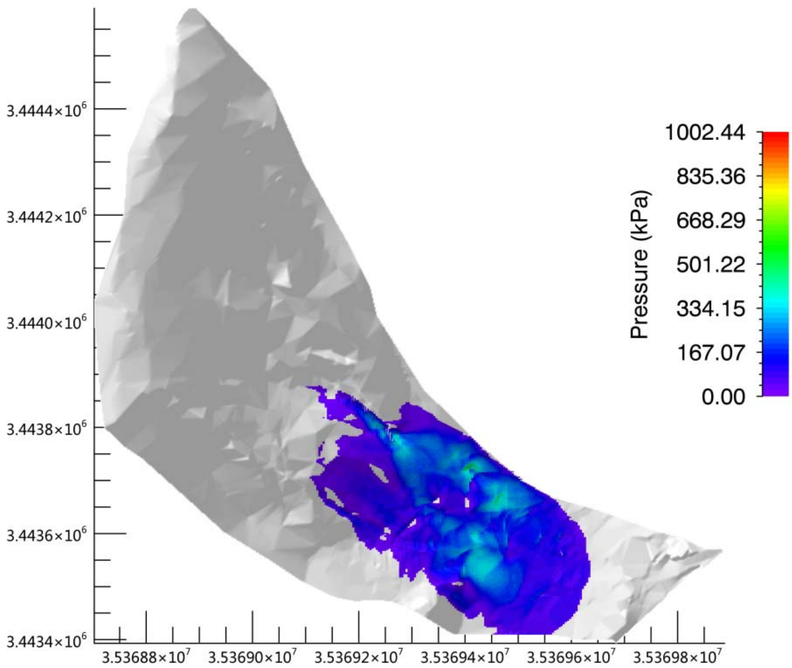




(a) ~~Thickness~~ Flow height



(b) ~~Speed~~ Velocity



(c) Pressure

Fig.~~6~~7 Movement characteristic parameters of Taziping landslide (before treatment)

See the kinematic characteristic parameters of the landslide deposits in Fig.~~6~~ 7. The coloredbar shows the maximum values of moving process or an instantaneous for a given time step. As shown by the calculation results, ~~①~~ deposits accumulated during the landslide movement process had a maximum ~~thickness~~ flow height of 23.85m, located around the surface gully of the middle and upper slope. The middle and lower of the landslide deposits had a ~~thickness~~ flow height of about 5-10m; ~~②~~ the middle and lower movement ~~speed~~ velocity of the landslide ranged from 3m/s and 7m/s; ~~③~~ the landslide had a mean pressure of about 500kPa, and the pressure of the middle and lower deposits was about 200kPa. Thus, three-story and lower houses within the deposition range might be buried, and it was further suggested that the design strength of the gable walls of houses on the middle and upper parts of the deposit be increased above 300kPa.

3.3 Hazard prediction after treatment

After fully accounting for the slide-resistant piles and mounds, we introduced the Morgenstern-Price method (Morgenstern et al., 1965) to calculate the stability coefficient of Taziping landslide after treatment. The method was determined with an iterative approaching by changing the position of the sliding surface until failure of the dumpsite (Fig.8). The physico-mechanical parameters under a saturated state (Hydrologic Engineering and Geological Survey Institute of Hebei Province, 2010) were adopted to search for the sliding plane of the landslide.

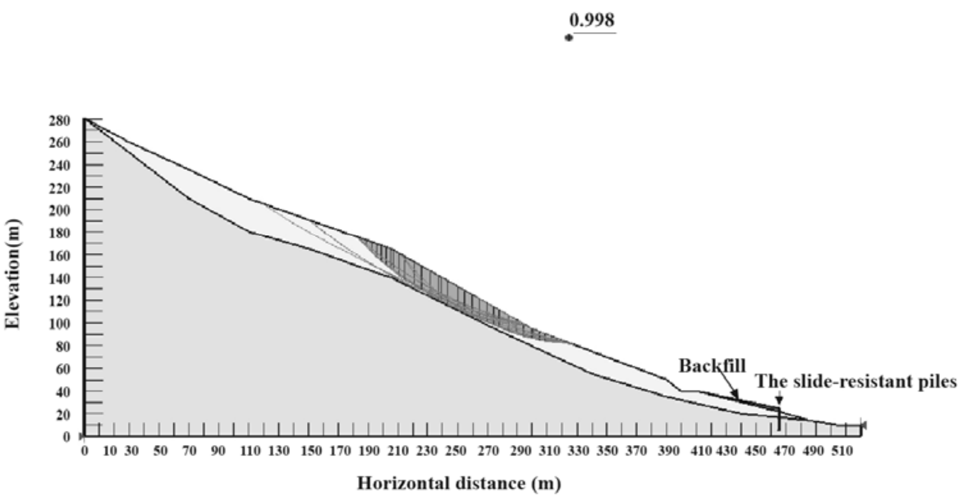
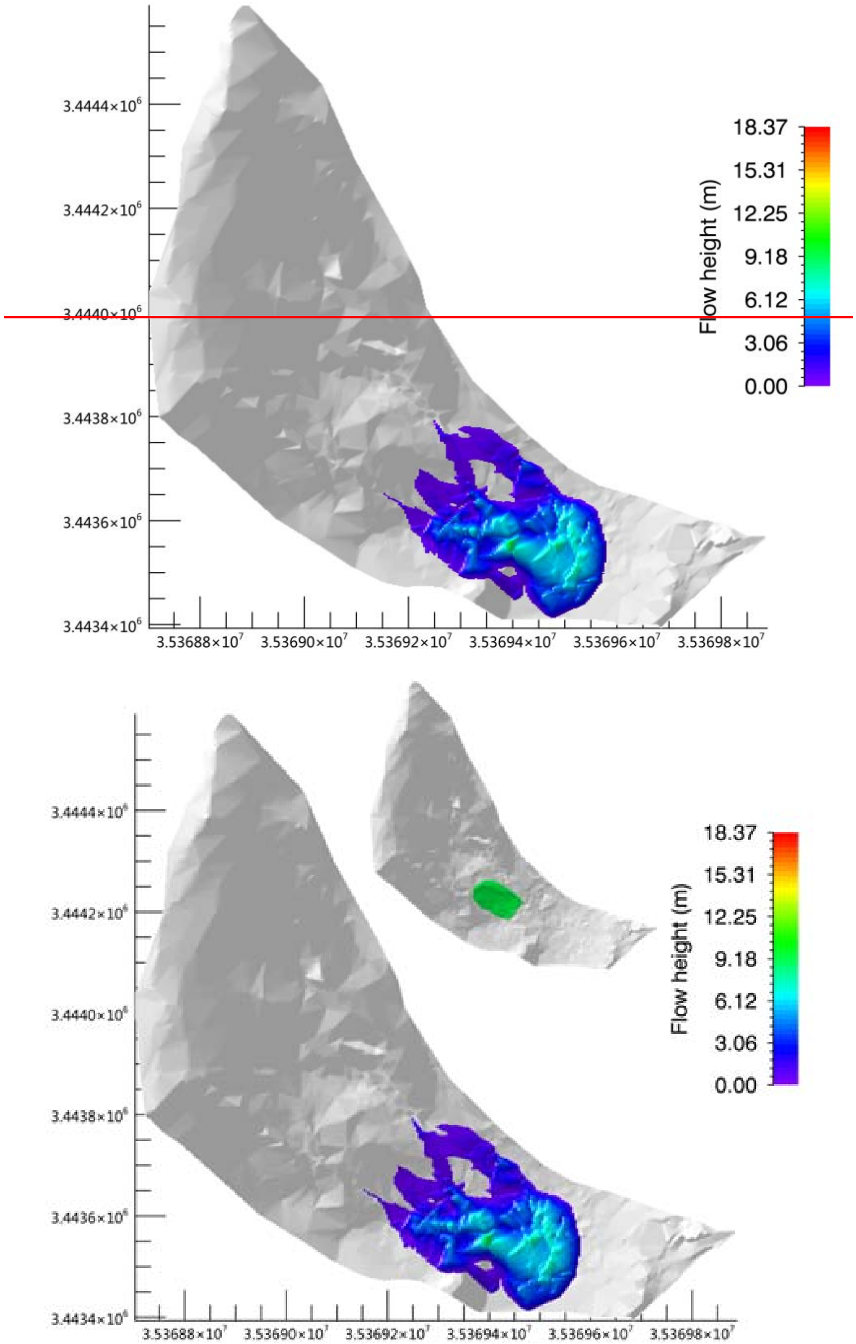
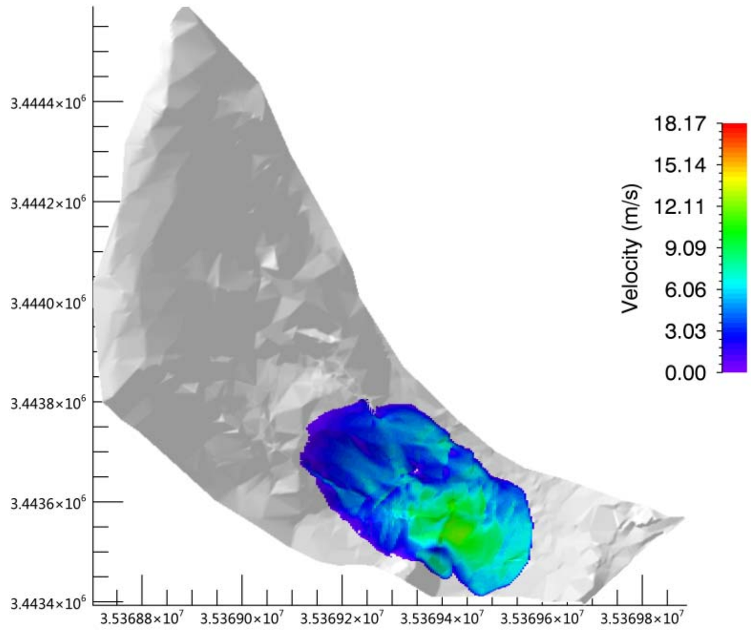


Fig.8 Search for the sliding plane of Taziping landslide (before treatment)

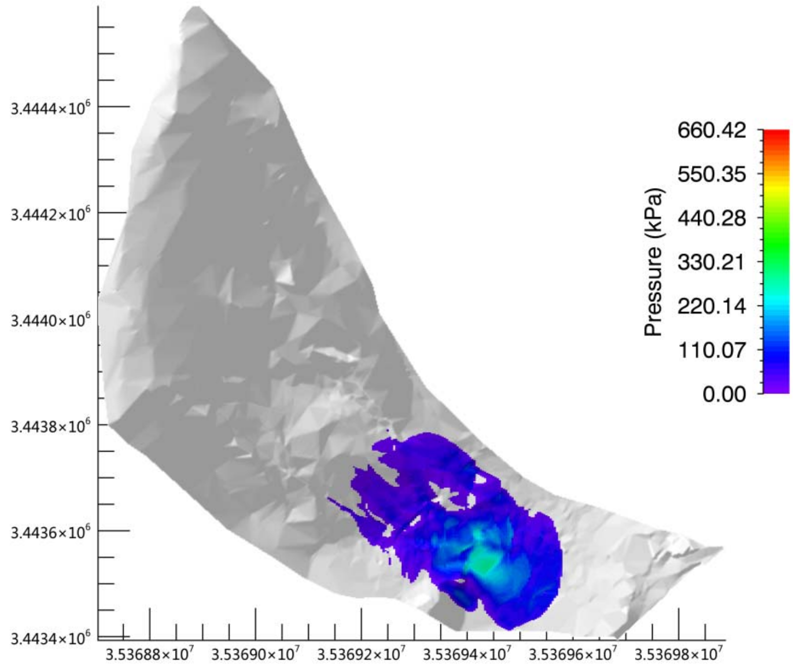
Based on the numerical analysis, the Taziping landslide stability coefficient was 0.998. it was found under rainfall conditions, the middle area of Taziping landslide was unstable. Loose deposits in the middle part of the landslide might convert into high-water landslide substances and cut out from the top of the slide-resistant piles. In the damaged area, the slope had a rear edge wall elevation of about 1,170m. Its front edge was located on the south side of the mountain road, with an elevation of ~~about 1,070m~~ 1,070-1,072m and a length of ~~about 180m~~182m. Thus, the scale of the rainfall-damaged is estimated to be about 250,000m^3, with a mean thickness of about 6m. The parameters in Tab.2 were again adopted for the simulated calculation.



(a) ~~Thickness~~ Flow height



(b) ~~Speed~~ Velocity



(c) Pressure

Fig.~~7~~ 9 Movement characteristic parameters of Taziping landslide (after treatment)

Provided in Fig.~~4~~ 9 are the kinematic characteristics of the landslide deposit. The coloredbar shows the maximum values of moving process or an instantaneous for a given time step.~~①~~ Deposits accumulated during the landslide movement process had a maximum ~~thickness~~ flow height of 18.37m, located around the surface gully of the middle and upper slope. Middle and lower of the landslide deposits had a ~~thickness~~ flow height of approximately 3-5m. ~~②~~ The middle and lower movement ~~speed~~

velocity of the landslide deposits ranged between 3m/s and 5m/s. ~~③~~ The landslide had a mean pressure of about 330kPa, and the pressure of the middle and lower deposits was about 100kPa. Thus, it could be held that two-story and lower houses within the deposition range might be buried. It was further suggested that the design strength of the gable walls of houses on the middle and upper parts of the deposits be increased above 150kPa.

After treatment, the accumulation ~~thickness~~ flow height and pressure of the deposits were reduced by about 1/2, and the kinematic speed was reduced by about 1/3. However, the Miaoba residential area of Red Village was still partially at hazard.

4 Results

Landslides reflect landscape instability that evolves over meteorological and geological timescales, and they also pose threats to people, property, and the environment. The severity of these threats depends largely on landslide speed and travel distance. There may be examples where entire houses on a landslide mass are moved but not destroyed because of stable base plates. In any case, velocity plays a more important role regarding kinetic energy acting on an obstacle. However, the Miaoba residential area of Red Village is located at the frontal part of Tazhiping lanslide. Then, ~~D~~during landslide movement, the spatial scale indexes of a landslide mass include area, volume, and thickness. The maximum thickness of the landslide is one of the direct factors influencing the building's deformation failure status. A large landslide displacement may lead to burial, collapse, or deformation failure of the building, and thus influence its safety and stability. Thus, landslide thickness constitutes an important index for assessing the hazards of a landslide disaster, and for influencing the consequences faced by disaster-affected bodies (Fell et al., 2008; DZ/T, 0286-2015). Provided in Tab.3 is a landslide thickness-based division of the predicted hazard zones of Taziping landslide, in which the thickness of the landslide mass correlates with the ability of a building to withstand a landslide disaster (Hungr et al., 1984; Petrazzuoli et al., 2004; GB, 50010–2010; Hu et al., 2012; Zeng et al., 2015). After treatment with slide-resistant piles, the hazard of a future slide was reduced by about 1/3 overall and by 2/3 in high-hazard zones.

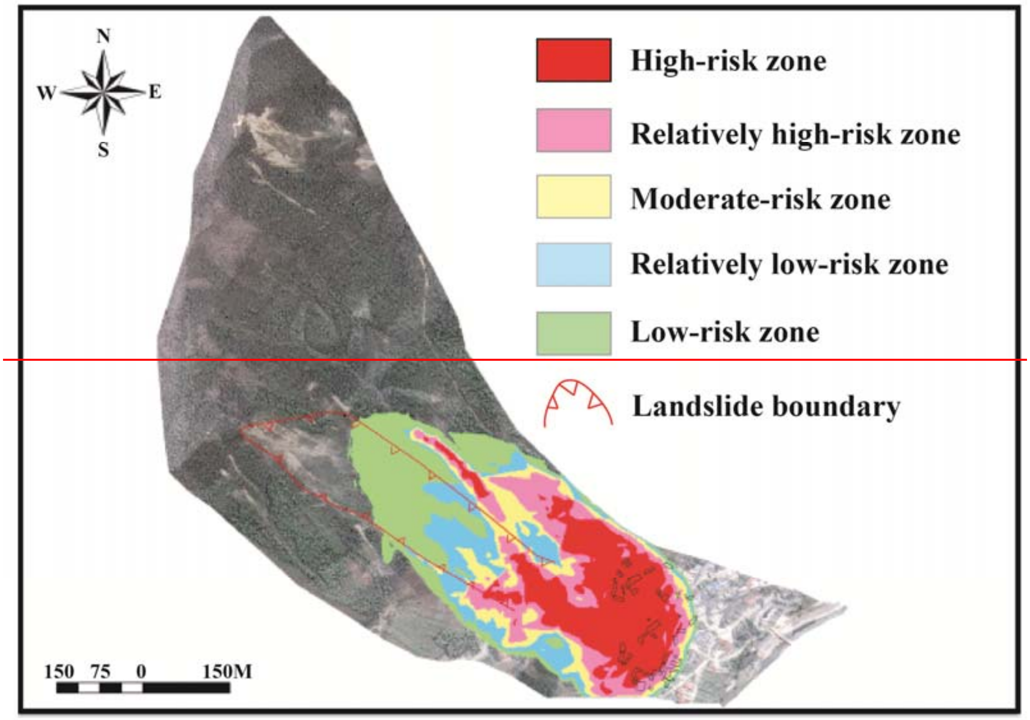
Tab.3 Division table of the predicted hazards of Taziping landslide (unit: m^2)

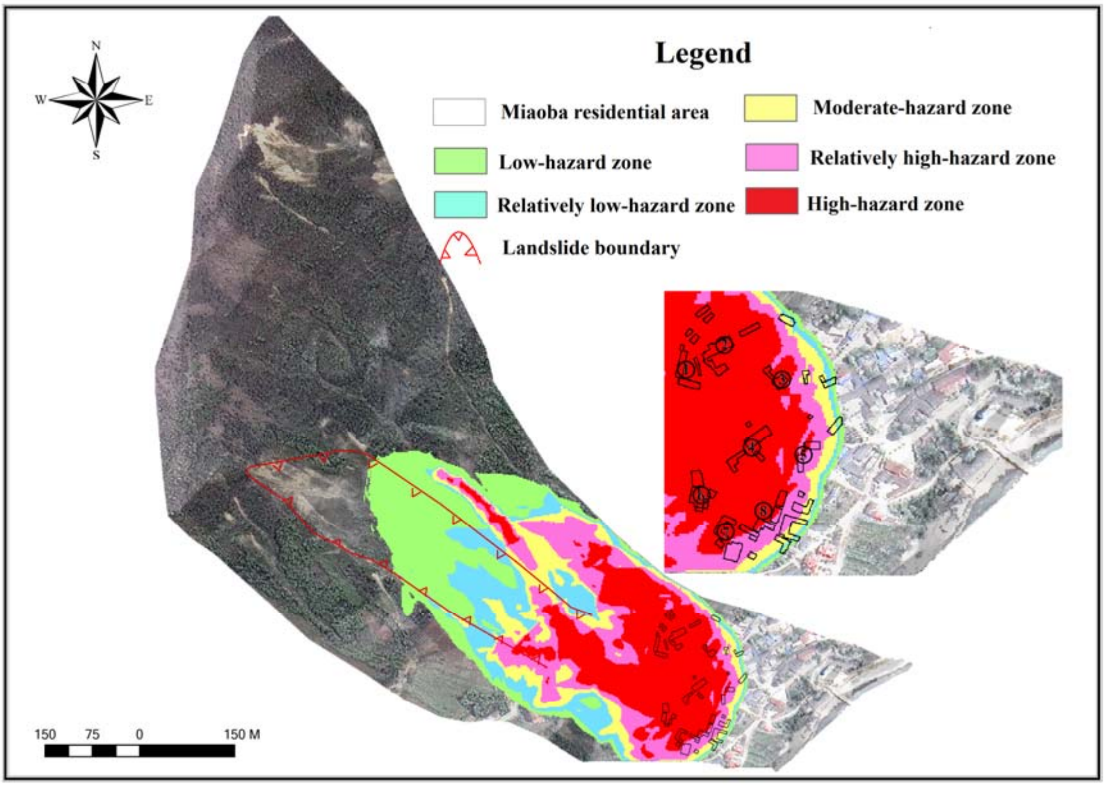
Hazard zone level	Assessment index	Building damage probability	Area before treatment	Area after treatment	Increased/decreased area	Building damage characteristics
Low-hazard zone (I)	$h \leq 0.5$m	20%	44，600	38，748	-5,852	One-story houses may be damaged; houses on the

						landslide mass are partially damaged.
Relatively low-hazard zone (II)	0.5 m＜ h≤1m	50~20%	24，900	26，400	+1,500	One-story houses have a very high probability of being ~~washed away~~ damaged; one-story houses on the landslide mass are completely damaged.
Moderate-hazard zone (III)	1m＜ h≤3m	80~50%	21，980	15，856	-6,124	One-story to three-story houses have a very high probability of being ~~washed away~~ damaged; houses less than three stories on the landslide mass are completely damaged.
Relatively high-hazard zone (IV)	3m＜ h≤5m	100~80%	30，820	19，636	-11,184	One-story houses may be buried, and two-story to six-story houses have a very high probability of being ~~washed away~~

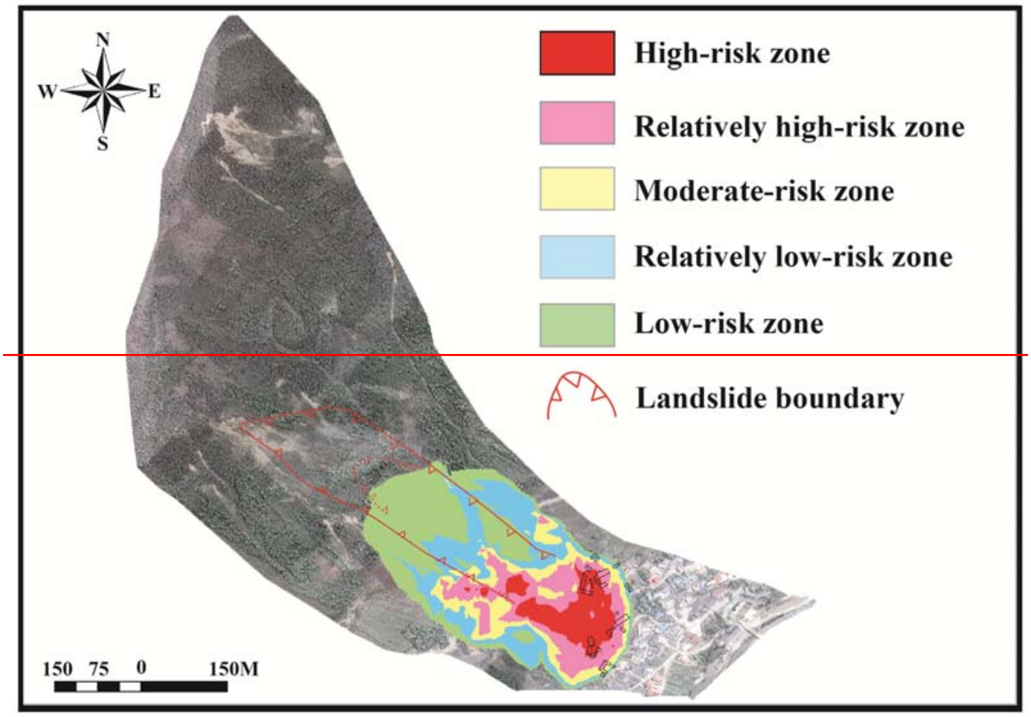
						damaged; houses on the landslide mass are completely damaged.
High-hazard zone (V)	*h*≥5m	100%	47，240	13，052	-34,188	Two-story and lower houses may be buried, and three-story and higher houses have a very high probability of being ~~washed away~~ damaged; houses on the landslide mass are completely damaged.
Total area:	—	—	169，540	113，700	-54,340	—

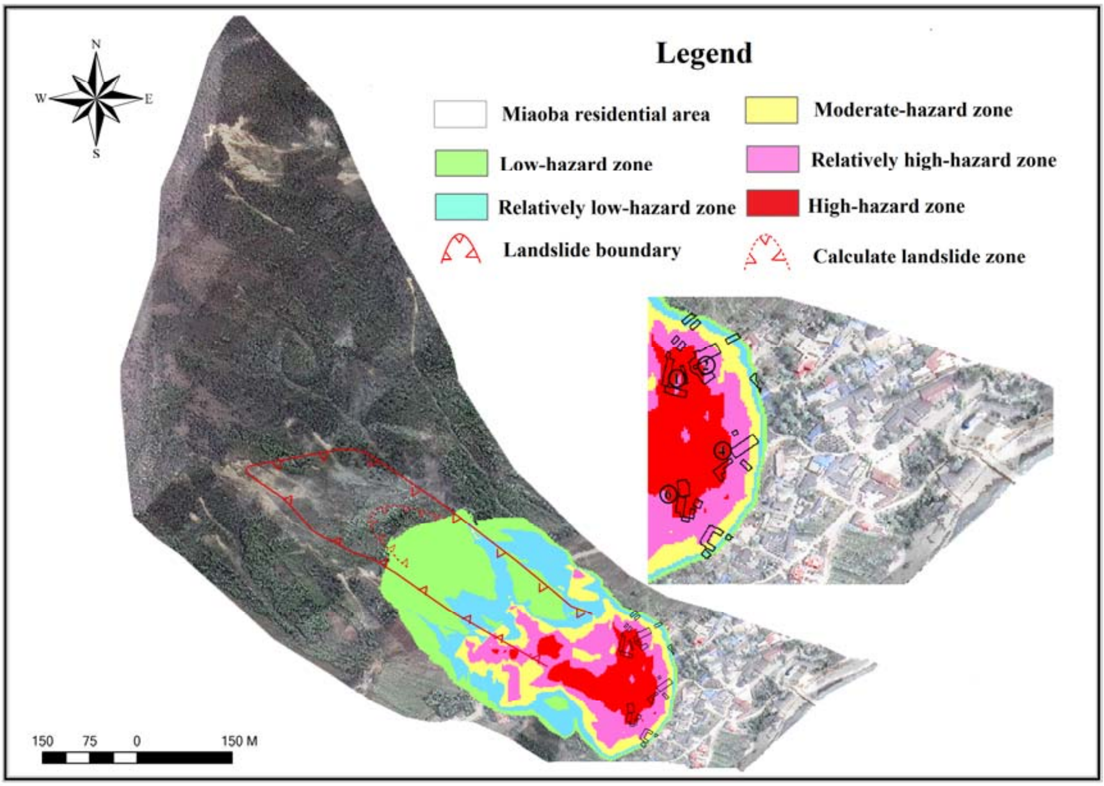
Given in Fig.~~8~~ 10 are the ~~3~~2D divisions of hazard zones of Taziping landslide before and after engineering treatment. The scope of the hazard zones changed before and after engineering treatment, particularly in the high-hazard zones. Before treatment with slide-resistant piles, the landslide posed a great hazard to eight houses on the left side of the upper Miaoba residential area, with high-hazard zone associated with landslide mass height over 5m and red zone. After treatment, the number of effected houses was reduced to four. We defined outside the colored area as no-hazard.





(a) Before treatment





(~~c~~b) After treatment

Fig.~~8~~10 ~~3~~2D division comparison of the hazards of Taziping landslide

5 Conclusions and Discussion

The hazard assessment of landslide using numerical models is becoming more and more popular as new models developing and becoming available in both scientific research and practical applications. There is some confusion about the mass movement process that is discussed and approached by the presented and adopted rheological model.

On the one hand, Landslides move downslope in many different ways (Varnes, 1978). In addition landslides can evolve into rapidly travelling flows, which exhibit characteristics of debris flows on unchannelized or only weakly channelized hillslopes. The geomorphic heterogeneity of rapid shallow landslides such as hillslope debris flows is larger than observed in channelized debris flows, however many of these flows can be successfully modelled using the Voellmy-fluid friction relation and starting the flow as a block release (Christen et al., 2012). This paper simulation results support this opition that Voellmy-fluid rheological model can also be used in the simulation of flow-type landslides.

On the other hand, The selection of model parameters remains one of the fundamental challenges for numerical calculations in natural hazards. At present, there are a high empirical parameters obtained from 30-year monitoring data on avalanche. Such as in RAMMS, we can automatically generate the friction coefficient of avalanche for our calculation domain based on topographic data analysis, forest information and global parameters and so on (WSL, 2013). The friction parameters of debris flow can found in some literature (Fannin et al., 2001; Iovine et al., 2003; Hürlimann et al., 2008; Scheidl et al., 2010; Huang et al., 2015). However, There are seldom cases researching on friction parameters of flow-type landslide. Therefore, we tested different coulomb friction coefficient μ values ranging between $0.1 \le \mu \le 0.6$ and viscous friction coefficient ζ values ranging between $100 \le \mu \le 1000 m \cdot s^{-2}$. Finally, we selected the coulomb friction coefficient $\mu = 0.45$ and viscous friction coefficient $\zeta = 500 m \cdot s^{-2}$ in accordance with back-analyses of well-documented landslide cases (Cepeda et al., 2010; Du et al., 2015). The results of the simulation results is consistent with the field observation in terms of topography and sliding path.

Based on the finite volume method and program RAMMS, the simulation results of Taziping landslide were consistent with the sliding path predicted by the field investigation. This correlation indicates that numerical simulation is an effective method for studying the movement processes of flow-type landslide~~ debris flows~~. The accumulation ~~thickness~~ flow height and pressure of landslide deposits were reduced by about 1/2, and the kinematic speed was reduced by about 1/3 after treatment. However, the Miaoba residential area of Red Village is still partially at hazard. Considering that two-story and lower houses within the deposition range might be buried, it was further suggested that the design strength of the gable walls of houses on the middle and upper parts of the deposit be increased above 150kPa.

By utilizing a GIS platform in combination with landslide hazard assessment indexes, we mapped the ~~3~~2D division of the Taziping landslide hazard zones before and after engineering treatment. The results indicated that overall hazard zones contracted after engineering treatment and, the area of high-hazard zones was reduced by about 2/3. After engineering treatment, the number of at hazard houses on the left side of the upper Miaoba residential area, was reduced from eight to four. It was thus clear that some zones are still at high hazard despite engineering treatment. Therefore, it was proposed that houses located in high-hazard zones be relocated or reinforced for protection.

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