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Vulnerability assessment model for buildings subjected to the impaction of landslides

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Outline

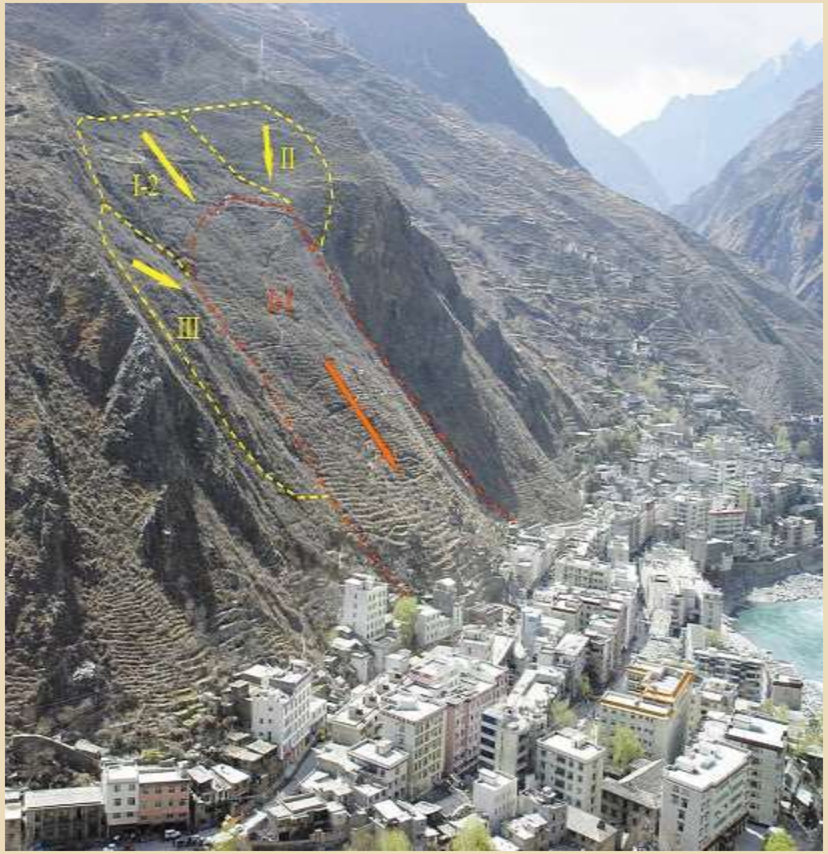
- ***Background***
- ***Experimental investigation on the spatial distribution of landslide intensity***
- ***Runout analysis model for 3D landslide***
- ***Resistance of exposed elements***
- ***Case study***
- ***Conclusions***

1.Background

◆Landslide can cause significant destruction in their path, often far from their point of origin. Prediction of post-failure motion is an essential component of hazard assessment.

◆Quantitative risk assessment for landslide hazards are increasingly being executed.

2014 Fengjie landslide, Chongqing,China



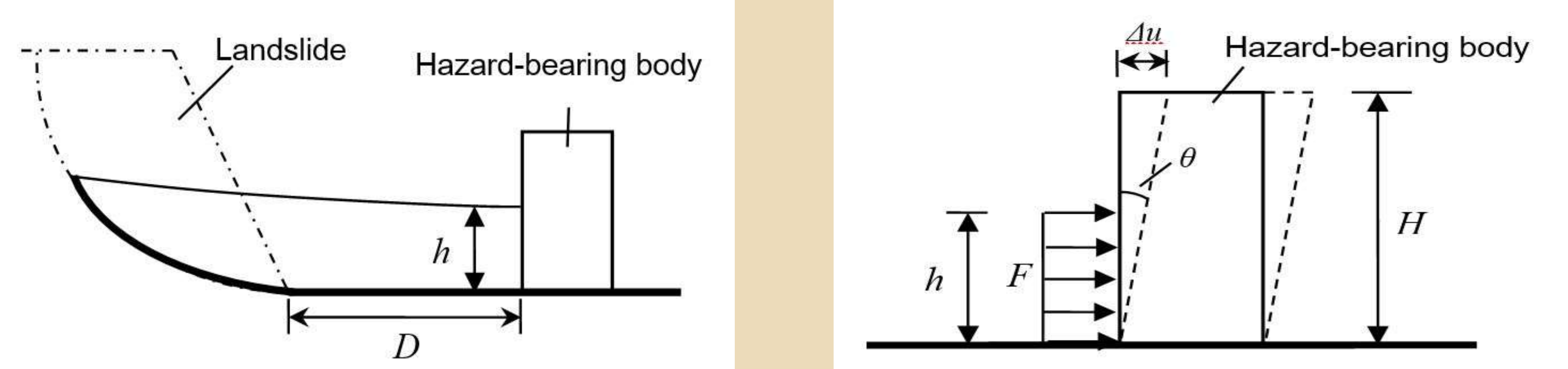
Panorama of the Danba landslide (Huang, 2009)

1.Background---problem statement

◆To make risk assessment for a individual landslide, it involves analyzing both the response of the element at risk and landslide intensity.

$$V = f(I,R) = \begin{cases} \dfrac{I}{R}, I \le R \\ 1, I > R \end{cases}$$

Landslide intensity ⟷ Response of the element at risk



Sketch of a structure impacted by a landslide

1.Background---Major trouble

The current prevailing modes predicting the post-failure motion of landslide and the interaction between landslide and buildings are empirical, which fail to give an explanation of the failure modes and the sliding body is viewed as deformable material in three-dimensional space.

- Spatial probability of landslide occurrence varies.
- It is obvious that different types of movement should have very quite different impacts force on elements.
- Meanwhile, different types of building elements have varied response for similar intensity of landslide.

1.Background---road map

- Experimental investigation on the interaction mechanism between sliding body and elements at risk is conducted.

- To predict the runout process, a three-dimensional spring-deformable-block model has been established.

- Three different failure modes for the RC columns in three-dimensional coordinate System and the vulnerability assessment of hazard-bearing body are discussed.

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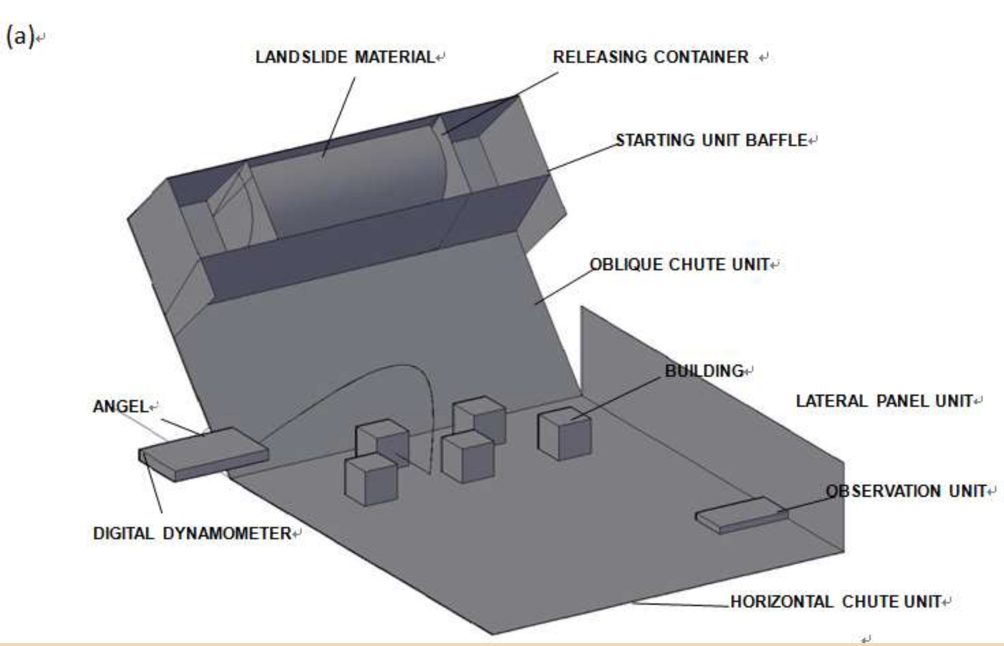
2. Experimental investigation on the spatial distribution of landslide intensity

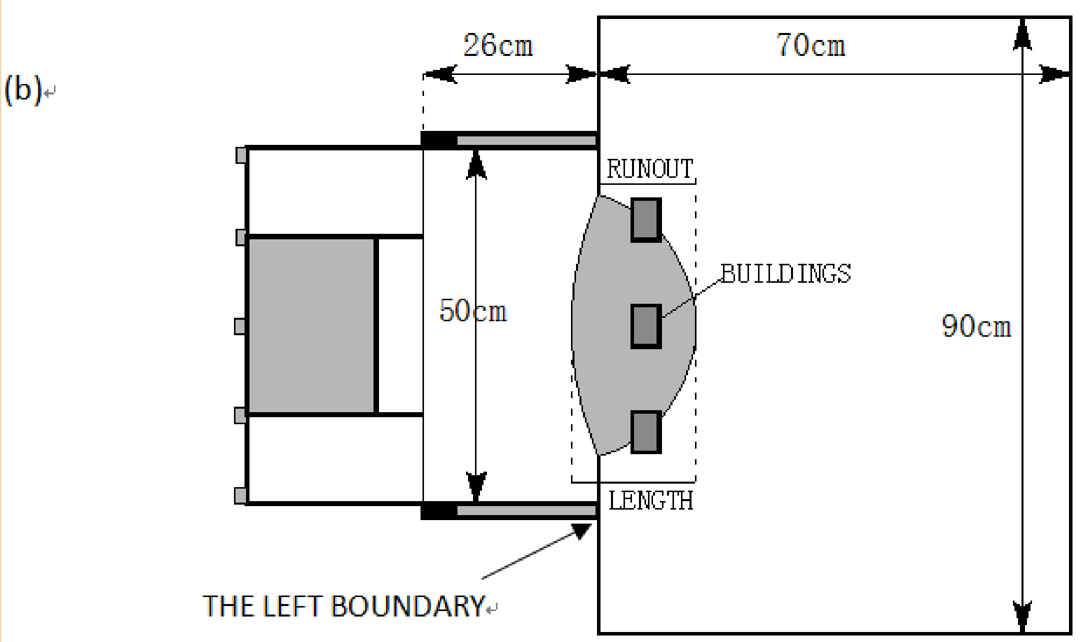
To find out the interaction mechanism between sliding body and buildings, we need make efforts on following aspects.

- Runout analysis is used to estimate the extent of the impact area and map the distribution of hazard intensity parameters, such as landslide velocity, flow depth, and depth deposits.
- Meanwhile, the impact velocity, impact force acting on buildings elements are measured to make quantitative risk assessment.

2. Experimental investigation on the spatial distribution of landslide intensity

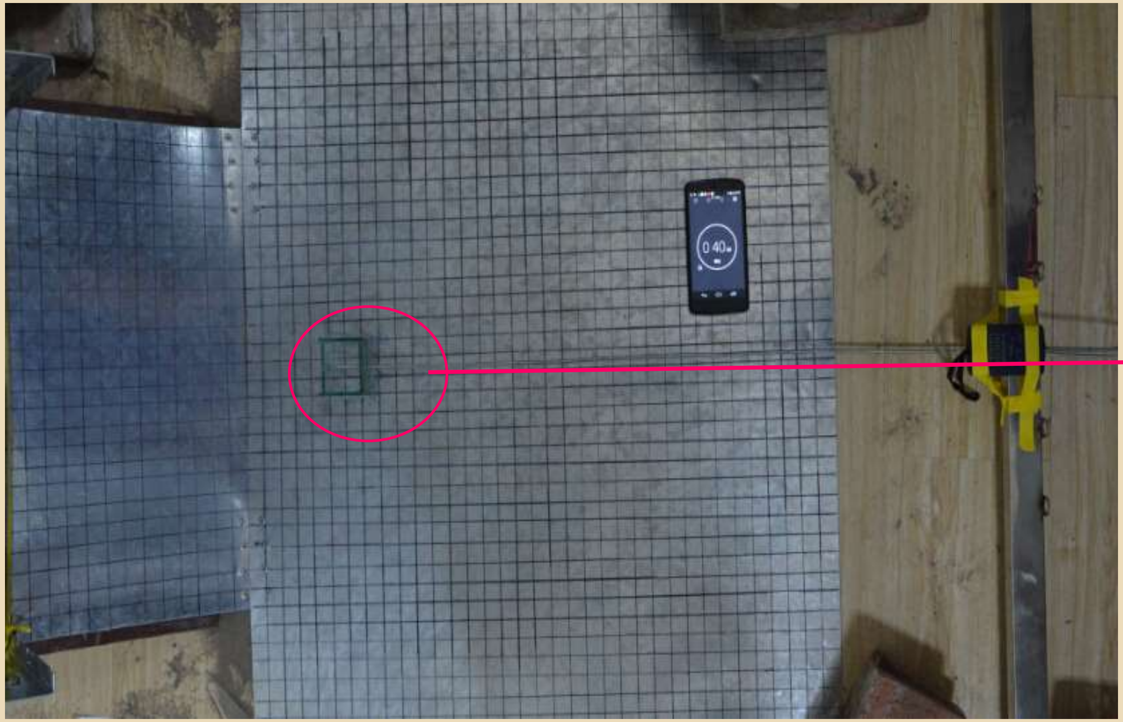
Experimental device consisting of releasing dry grain debris onto an oblique chute were designed.

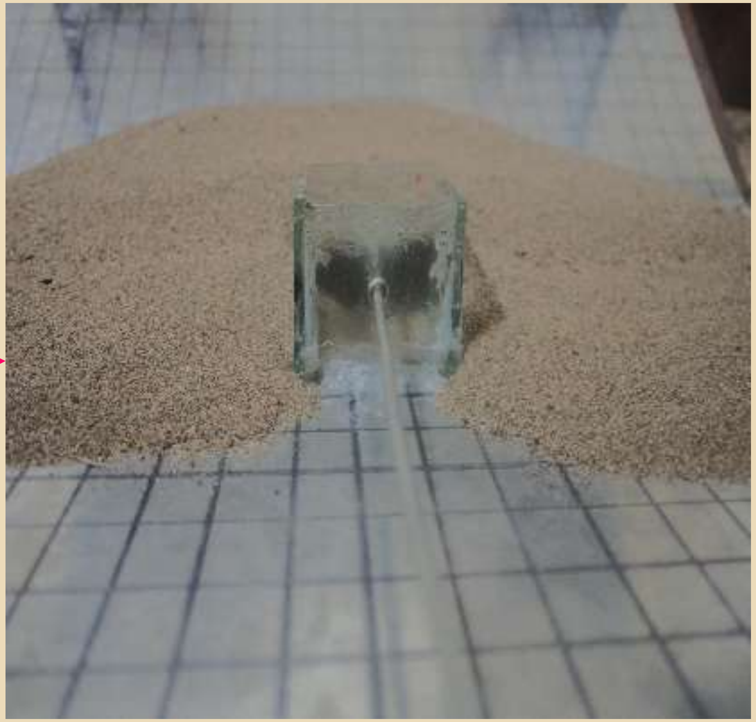




As depicted in the figure, an observation unit which comprised of high-speed camera and digital dynamometer for measuring the structural impact force is used.

2. Experimental investigation on the spatial distribution of landslide intensity



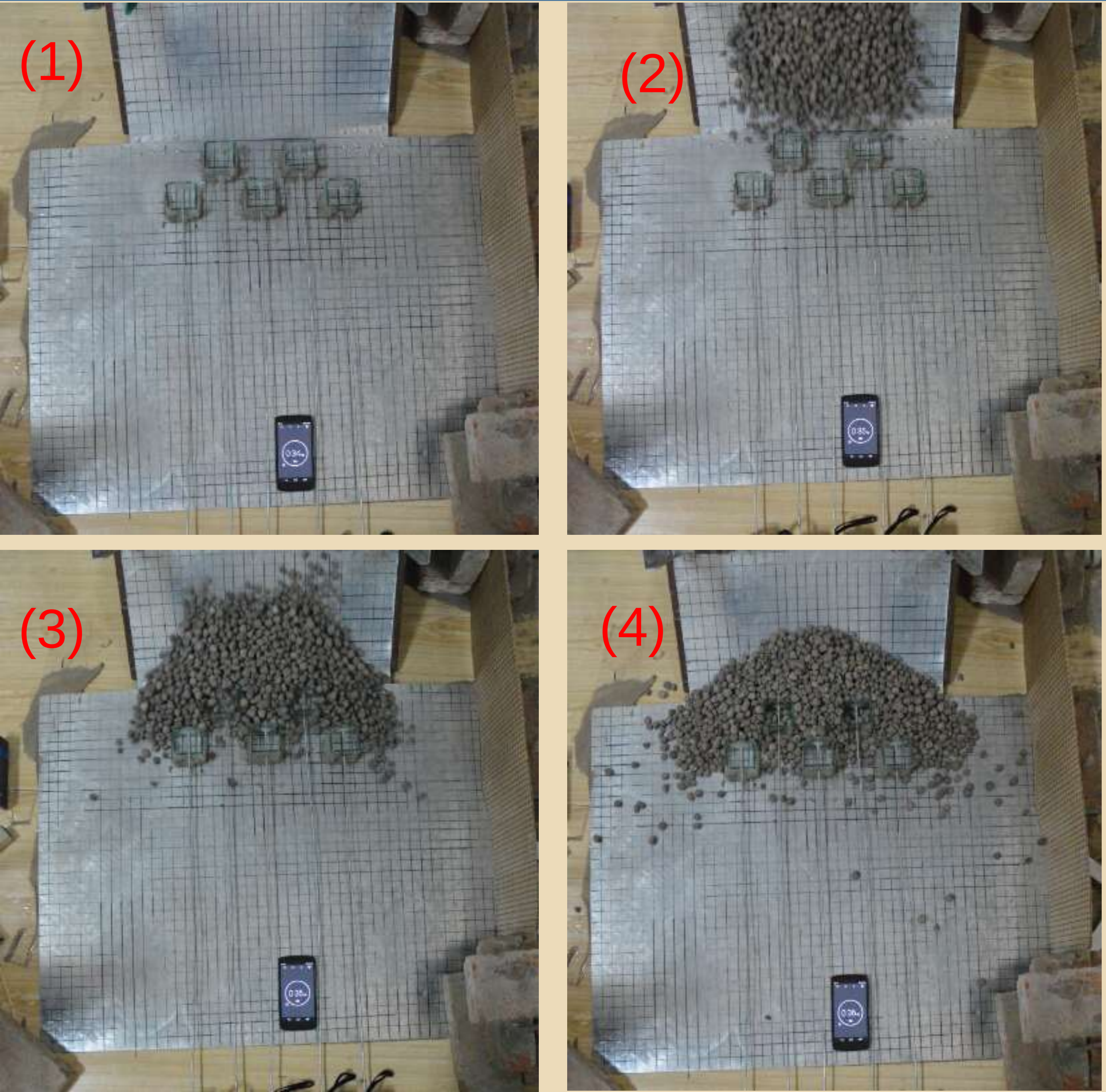


- The buildings composed of glass blocks were fixed on the horizontal chute unit with the exception of the front block.
- The front glass block was connected to a straight wire extending from the hole, and the straight wire was connected to the digital dynamometer through the hole in the middle of the posterior glass blocks.

2. Experimental investigation on the spatial distribution of landslide intensity

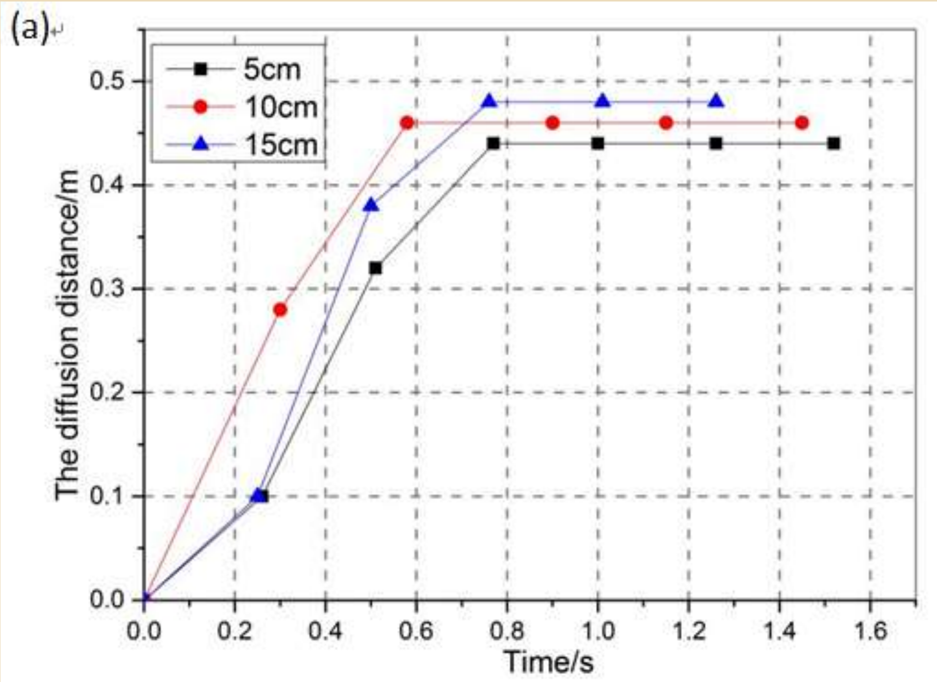
By using high speed camera, the change in diffusion distance with time, the final diffusion area, the impact force on the buildings and the height of the impacting point could be obtained respectively.

2. Experimental investigation on the spatial distribution of landslide intensity

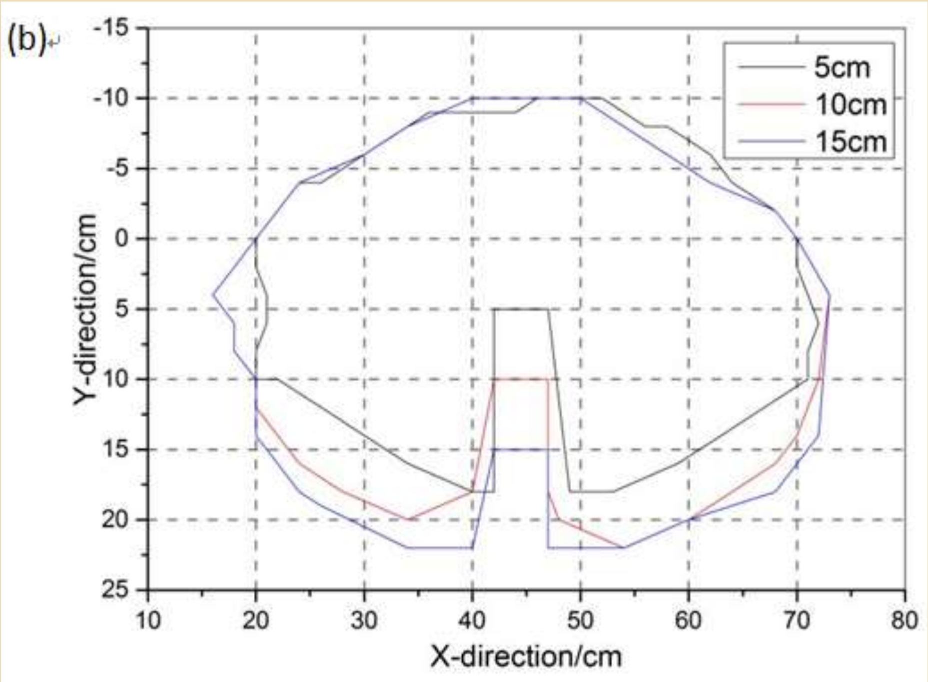


- By controlling various parameters, i.e., the oblique chute angle, the material of sliding body, the installation distance of buildings, the interaction between the landslide instability and the interaction process mechanism of landslides impacting on the buildings was determined.

2. Experimental investigation on the spatial distribution of landslide intensity



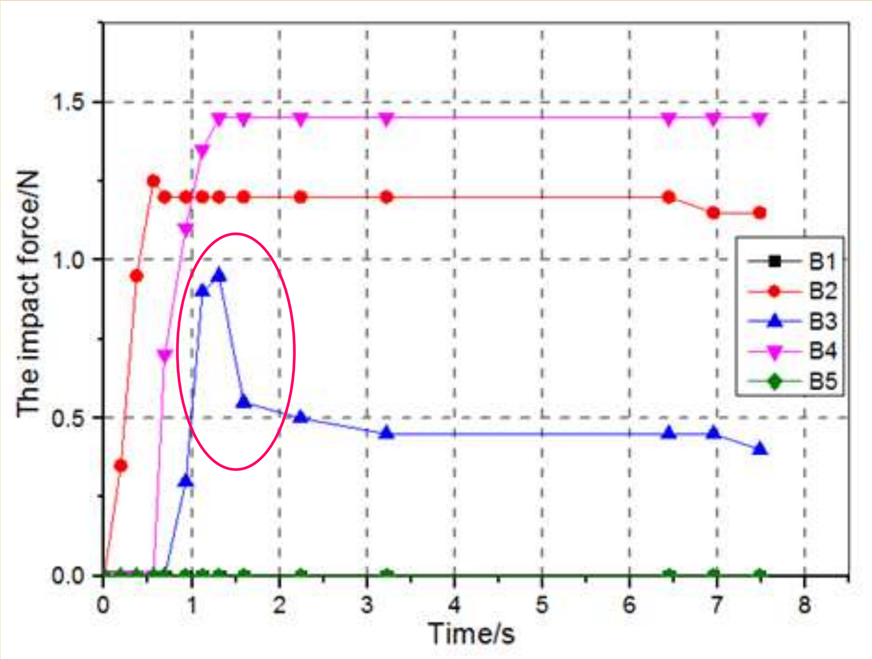
The diffusion distance evolution

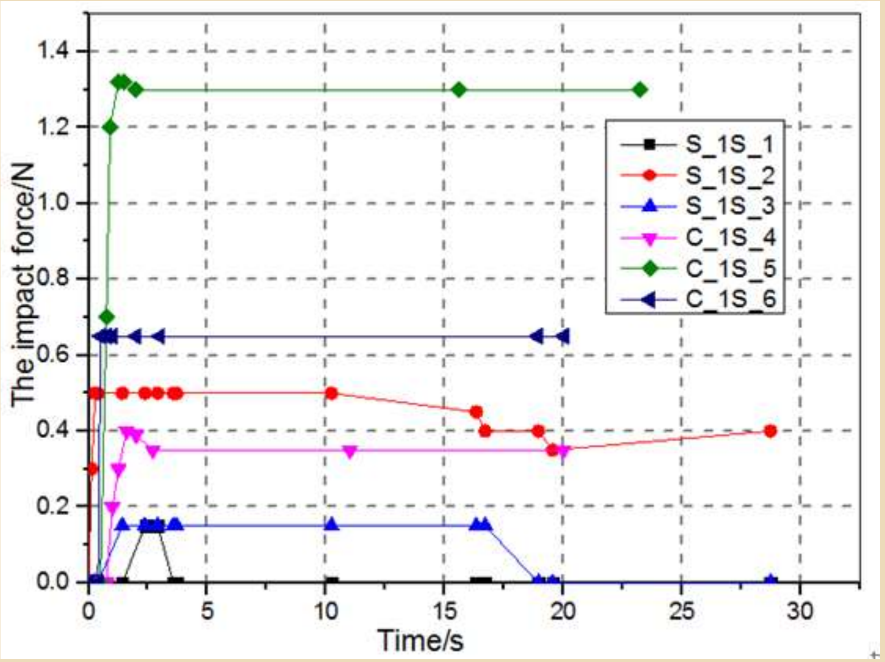


Comparison of diffusion area for different distance

- A larger distance between the horizontal chute and the building contributes to the increase of the maximum diffusion distance and diffusion area. For a larger interval space, the potential energy is converted to kinetic energy more effectively and hence the flowing behavior of the sliding mass can develop sufficiently.
- The maximum diffusion distance and diffusion area are increased. Otherwise, the time cost for reaching the maximum diffusion distance decreased.

2. Experimental investigation on the spatial distribution of landslide intensity

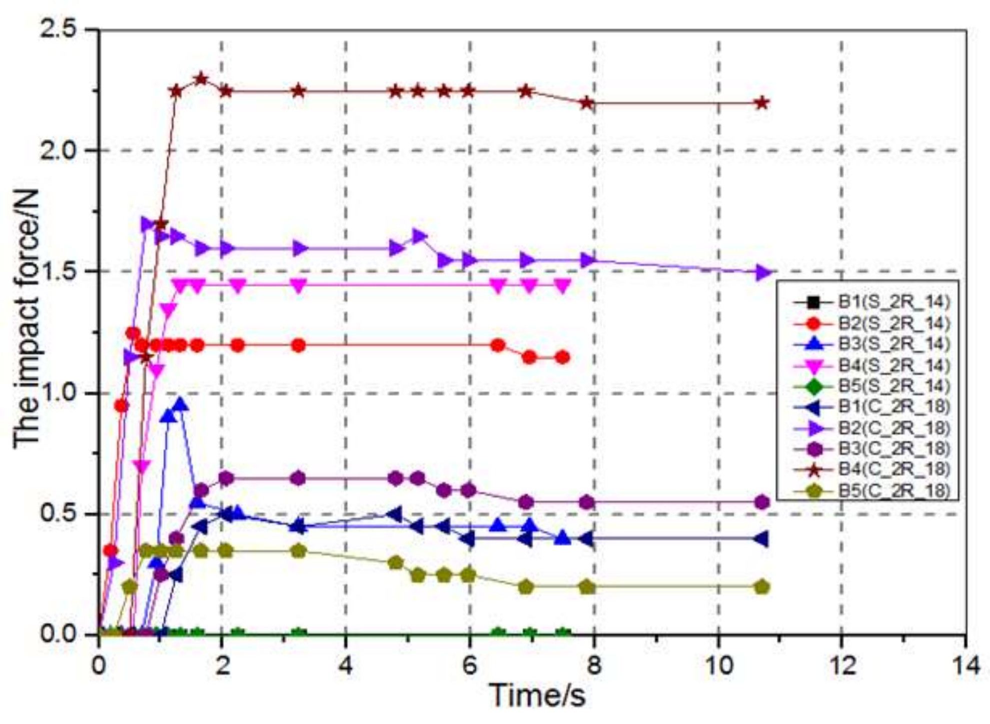




The impact force of sand and ceramsite on a single building.

- The impact force of coarse particle on the building was greater than that of the fine one at very close distance, but for farther distance the impact force values are getting closer.

2. Experimental investigation on the spatial distribution of landslide intensity



The impact force with different material

- The impact on the model buildings increased rapidly to a peak value over a short time, then decreased and finally stabilized to a constant value.

- Similar impact force could be observed for the buildings located in the front row, whereas buildings located in the back row had different impact values.

2. Experimental investigation on the spatial distribution of landslide intensity

Vulnerability value (V)	Disaster level	Damage description
0	No damage (Ⅰ)	There is a large distance between the building and the stable sliding body, no damage to the building
0-0.2	Some sedimentation (Ⅱ)	Sediment-laden water enters building's main floor or basement; requires renovation; up to 25% insured loss
0.2-0.4	Some structural damage (Ⅲ)	Some supporting elements damaged and could be repaired with major effort; 25–75% insured loss
0.4-0.6	Major structural damage (Ⅳ)	Damage to crucial building-supporting piles, pillars and walls; will likely require complete building reconstruction; 75% insured loss
0.6-1	Complete destruction (Ⅴ)	Structure is completely destroyed and/or physically transported from original location; 100% insured loss

disaster level and characteristics

➢The minimum vulnerability value in the case of a single building was 15 cm, thus we can presume that the safety distance between the building and the horizontal chute unit is more than 15 cm under general conditions.

Vulnerability values of hazard-bearing buildings and disaster levels for the case of a single building

Installation distance of building	5 cm	10 cm	15 cm
$I'_{DF}=v'd'^2$	116.44	60.5	28.13
$I_{DF0}=v_0 d_0^2$	0.538	0.28	0.13
Disaster level	Major structural damage (Ⅳ)	Some structural damage (Ⅲ)	Some sedimentation (Ⅱ)

2. Experimental investigation on the spatial distribution of landslide intensity

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Residential building disaster level and characteristics

Vulnerability values of hazard-bearing buildings and disaster levels for a group of buildings

Building number	B1	B2	B3	B4	B5
$I'_{DF}=v'd'^2$	60	187.5	60	187.5	93.75
$I_{DF0}=v_0 d_0^2$	0.277	0.866	0.433	0.866	0.277
Disaster level	Some structural damage (Ⅲ)	Complete destruction (Ⅴ)	Major structural damage (Ⅳ)	Complete destruction (Ⅴ)	Some structural damage (Ⅲ)

- Not only the interaction between sliding body and buildings, but also the interaction between neighbouring buildings should be taken into account.

- The vulnerability value and impact velocity in a group were higher than those in the other cases.

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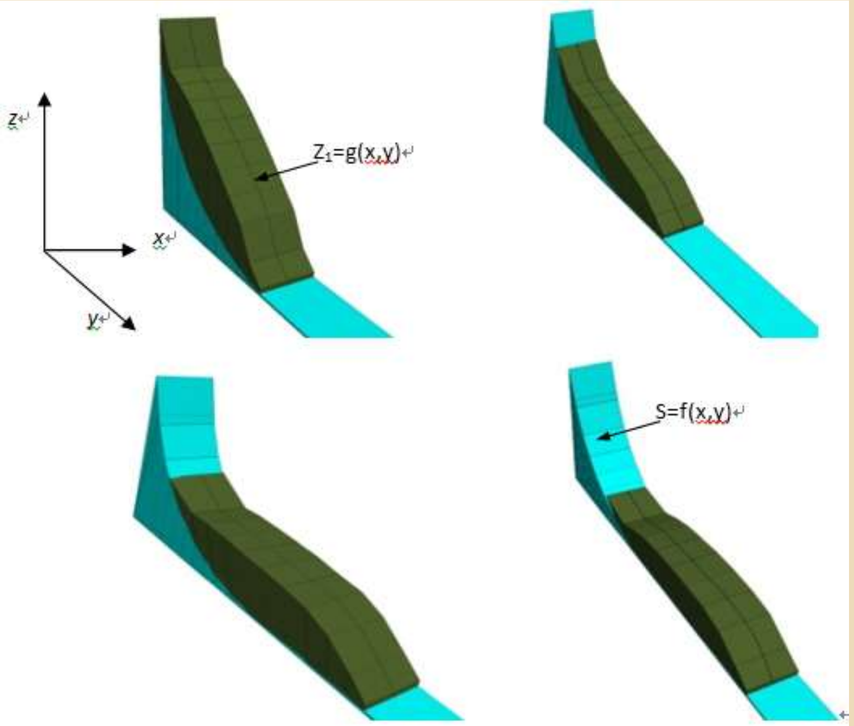
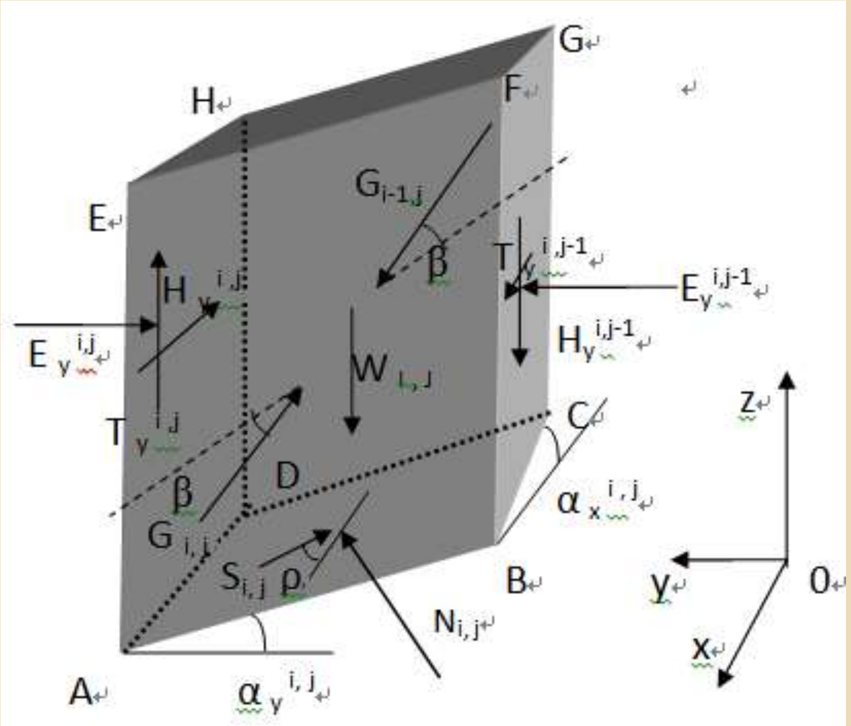
3. Runout analysis model for 3D landslide

◆To investigate the dynamic runout process of the landslide across a 3D terrain, a three-dimensional model using spring-deformable-block model is proposed.



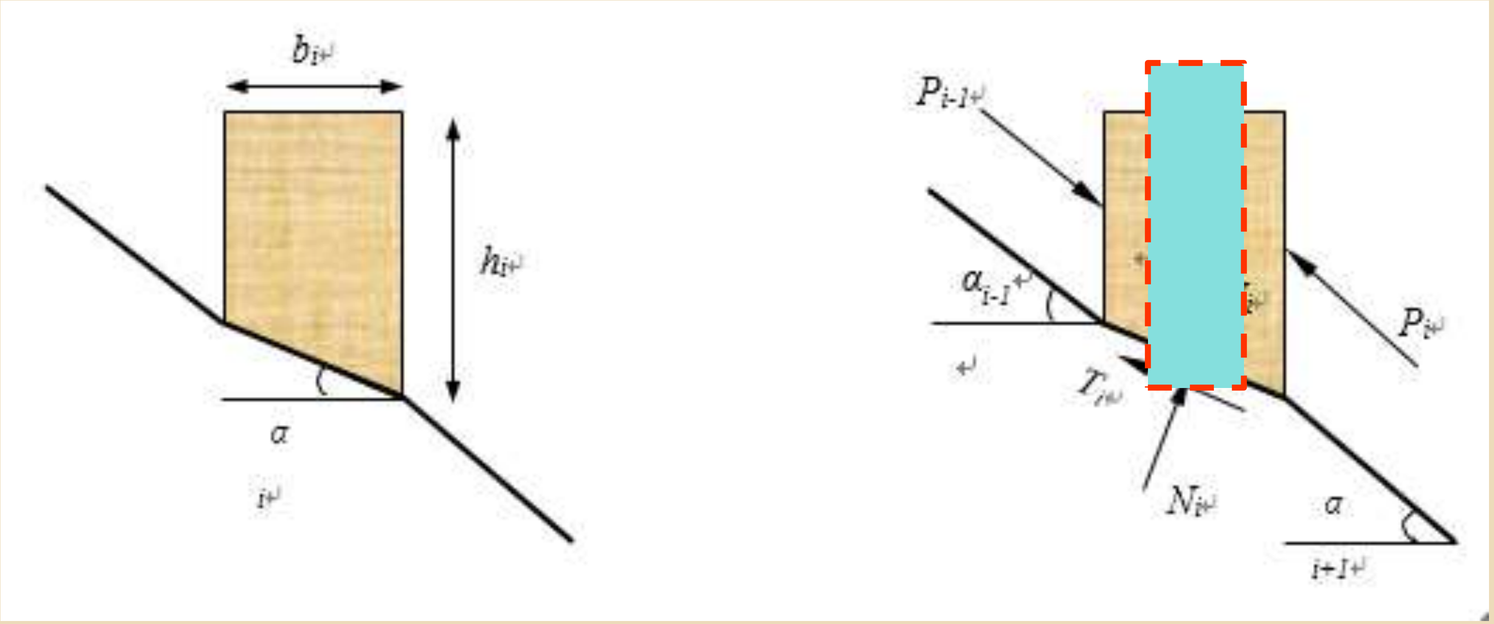
Sketch of three dimensional landslides motion



The simplified forces analysis of column

3. Runout analysis model for 3D landslide

- The sliding body is simplified as multi rigid blocks, linked with Gravity-free springs which only endure the horizontal forces.
- The inter-column forces and the relevant deformation energy are expressed in the way as the internal forces and deformation energy of springs, respectively.
- Moreover, the change in the width of the columns is expressed as the deformation of springs.



Simplified model of three-dimensional sliding

3. Runout analysis model for 3D landslide

- The width variation of the column (i,j) at the moment t=0 can be written as

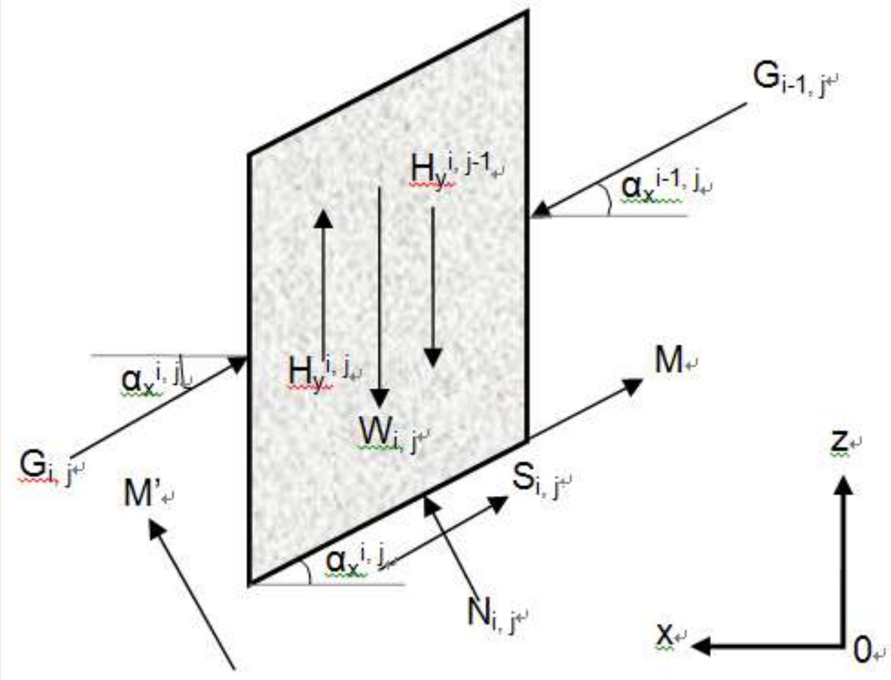
$$s_{x,0}^{i.j} = \frac{\sigma_{x,0}^{i,j}}{E_0} e_{i,j}^{0} = \frac{P_{x,0}^{i,j} e_{i,j}^{0}}{E_0 h_{i,j}^{0} b_{i,j}^{0}} \quad (1)$$

- For the spring which captures the same width variation $s_x^{i,j}$, the deformation energy can be expressed as

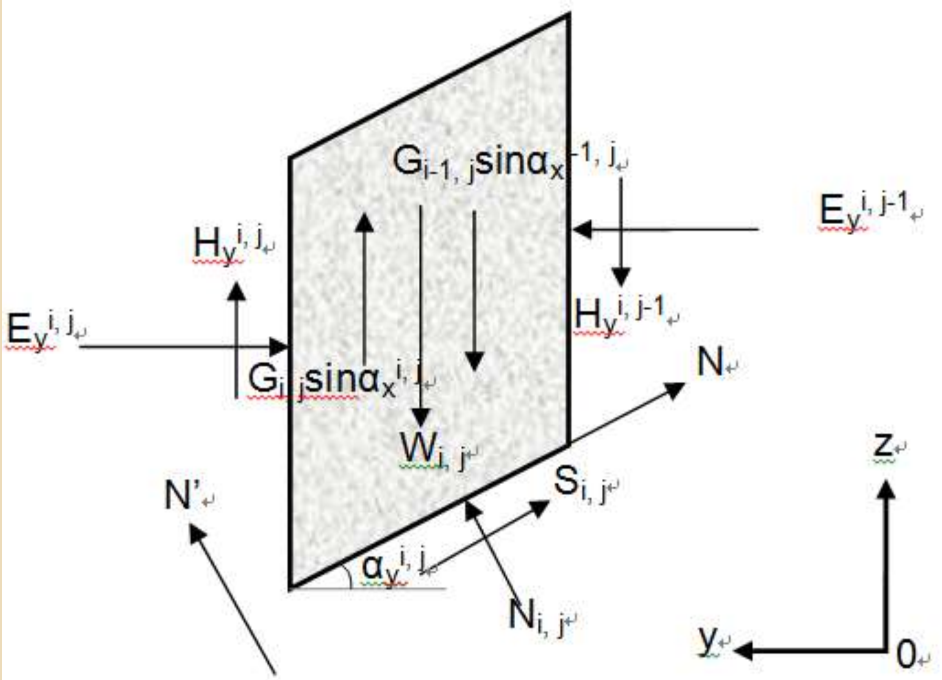
$$E_x^t = \frac{1}{2} k_x^{i,j} (s_{x,0}^{i,j})^2 = \frac{k_x^{i,j} \left(P_{x,0}^{i,j} e_{i,j}^{0}\right)^2}{2\left(E_0 h_{i,j}^{0} b_{i,j}^{0}\right)^2} \quad (2)$$

3. Runout analysis model for 3D landslide

◆According to the principle of transmitting coefficient method, the residual sliding force can be obtained as follows.



Projection of the forces of a column on *xoz* surface



Projection of the forces of a column on *yoz* surface

3. Runout analysis model for 3D landslide

- During the process of sliding, the medium of the sliding body is continuous. Therefore, the acceleration of adjacent particles inside the sliding body change continuously. We assume that the acceleration of the particles on the adjacent interface between columns vary linearly along the direction of the width .

- Based on the kinematics theory, the equation of the force equilibrium parallel to the slip surface can be expressed as

$$
\begin{aligned}
m_{i,j} a_{x,t}^{i,j} &= G_{i-1,j}^{t} \cos(\alpha_{x}^{i-1,j} - \alpha_{x,t}^{i,j}) + H_{y,t}^{i,j-1} \sin \alpha_{x,t}^{i,j} + W_{i,j} \sin \alpha_{x,t}^{i,j} \\
&+ (S_{i,j}^{t} m_{x}^{t} + N_{i,j}^{t} n_{x}^{t}) \cos \alpha_{x,t}^{i,j} - G_{i,j}^{t} - H_{y,t}^{i,j} \sin \alpha_{x,t}^{i,j} - (S_{i,j}^{t} m_{z}^{t} + N_{i,j}^{t} n_{z}^{t}) \sin \alpha_{x,t}^{i,j}
\end{aligned}
\tag{18}
$$

3. Runout analysis model for 3D landslide

- It is reasonable to assume the acceleration as a constant during the period (t,t+△t) if increment △t is small enough. Therefore, the velocity of the column at moment t+△t can be written as

$$v_{x,t+\Delta t}^{i,j} = v_{x,t}^{i,j} + a_{x,t+\Delta t}^{i,j} \cdot \Delta t \tag{24}$$

- The acceleration of the particle on the interface of the column (i,j) and the column (i+1,j) in the *x* direction can be expressed as

$$a1_{x,t}^{i,j} = a_{x,t}^{i,j} - \frac{e_{i,j}^{t}}{e_{i,j}^{t} + e_{i+1,j}^{t}}(a_{x,t}^{i,j} - a_{x,t}^{i+1j}) \tag{25}$$

The width of the column (i,j) in the *x* direction at moment t,t+△t

$$e_{i,j}^{t+\Delta t} = d_{x,t+\Delta t}^{i,j} - d_{x,t+\Delta t}^{i-1,j} + e_{i,j}^{0}$$

$$d_{x,t+\Delta t}^{i,j} = \left[v_{x,t}^{i,j} \cdot \Delta t + \frac{1}{2} a1_{x,t}^{i,j} \cdot (\Delta t)^2 \right] \cos\alpha_{x,t}^{i,j}$$

$$d_{x,t+\Delta t}^{i-1,j} = \left[v_{x,t}^{i-1,j} \cdot \Delta t + \frac{1}{2} a1_{x,t}^{i-1,j} \cdot (\Delta t)^2 \right] \cos\alpha_{x,t}^{i-1,j}$$

The displacements of the particles on the two boundary faces of the column in the *x* direction

- The volume of every column is invariable, described as

$$h_{i,j}^{0} b_{i,j}^{0} e_{i,j}^{0} = h_{i,j}^{t} b_{i,j}^{t} e_{i,j}^{t} \tag{26}$$

$$h_{i,j}^{t+\Delta t} = \frac{h_{i,j}^{0} b_{i,j}^{0} e_{i,j}^{0}}{b_{i,j}^{t+\Delta t} e_{i,j}^{t+\Delta t}} \tag{27}$$

The height of the column (i,j) at moment t+△t

3. Runout analysis model for 3D landslide

◆Calculation algorithm

STEP1 Divide the sliding body and calculate the weight of each column.

STEP2
transmitting coefficient method

STEP3 Obtain the velocity of the column in both directions at moment t+ △t (Kinematic analysis)

STEP4 Obtain the deformation and inter-column force of the column in both directions at moment t+ △t (Elastic deformation analysis).

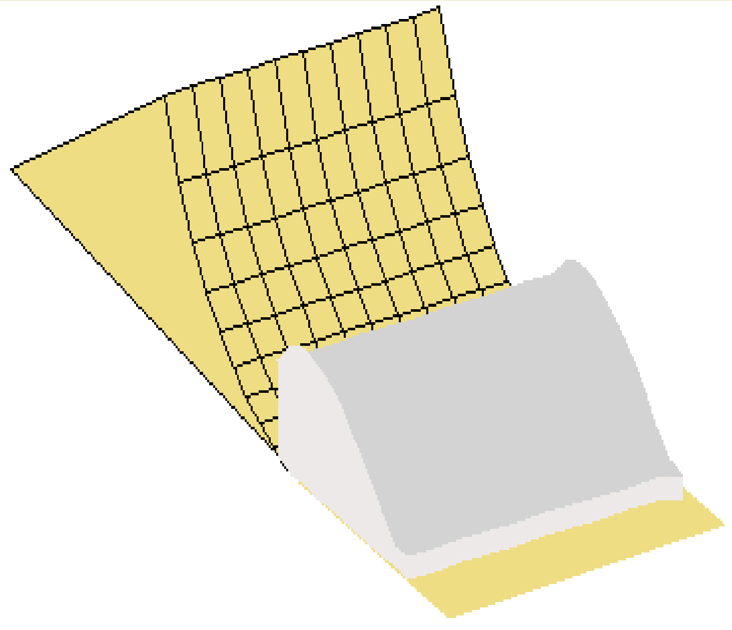
STEP5 Obtain the normal force of the column on the slip surface at moment t+ △t

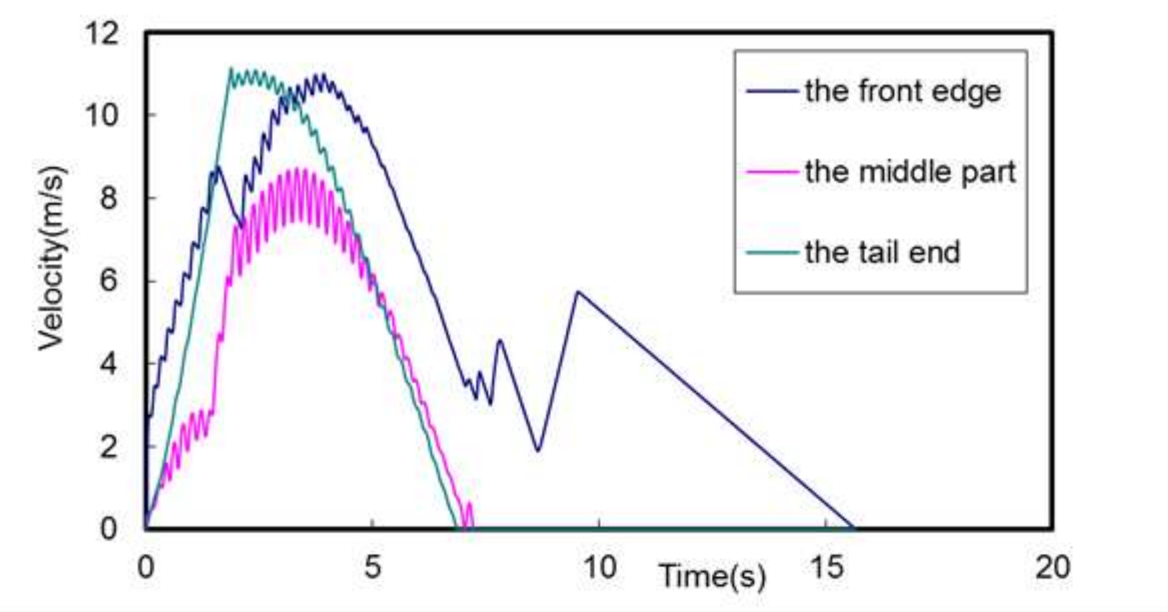
STEP6 Obtain the acceleration of the column in both directions at moment t+ △t

STEP7 Obtain the velocity, the inter-column force and the acceleration of each column at periods such as t+ △t , t+ 2△t , …….., t+ n△t looping the steps 3-6.

3. Runout analysis model for 3D landslide

Comparison the runout process obtained from the present model with the discrete element method has been made.





The time history of the velocity at different location of the sliding body

The varying trends of the velocity compare reasonably well with DEM and there exist apparent oscillations in both methods during the variation of the velocity.

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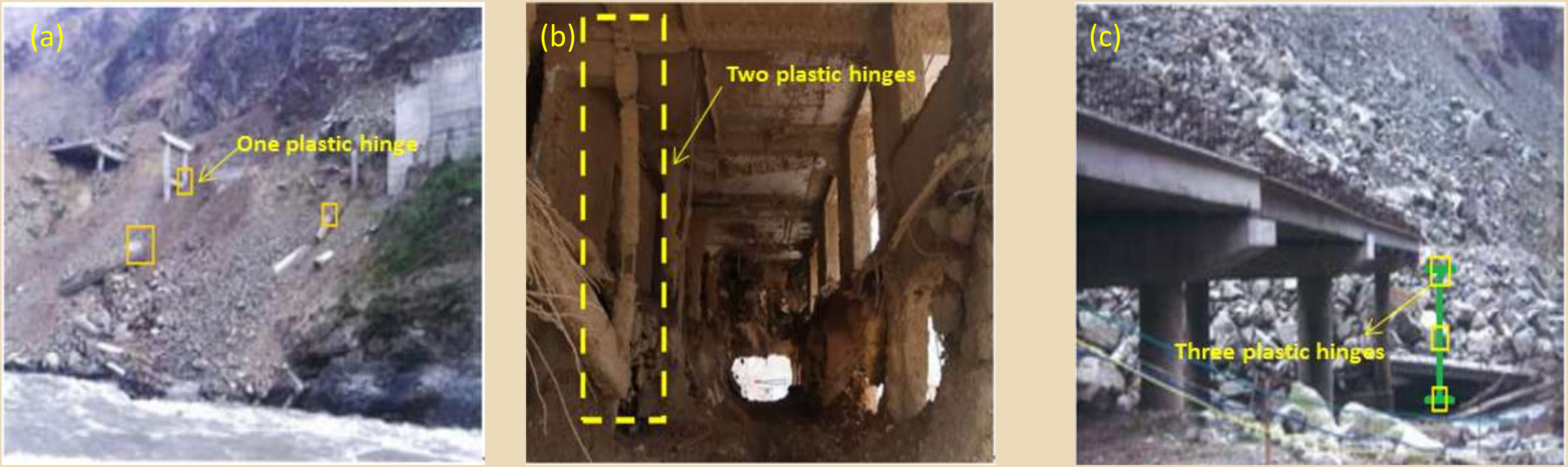
4. Resistance of exposed elements

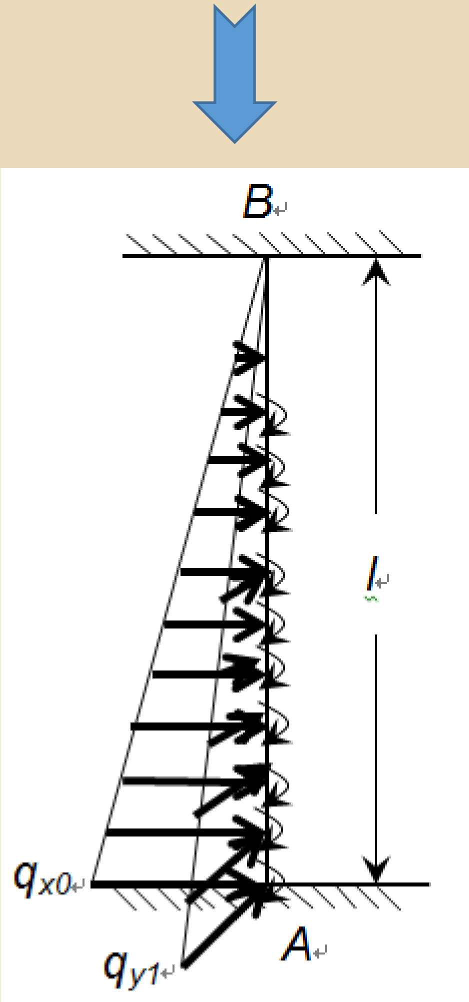
◆Based on example investigation, this research categorized the failure modes of the column into three typical types, which are one plastic hinge, two plastic hinges and three plastic hinges model, respectively.



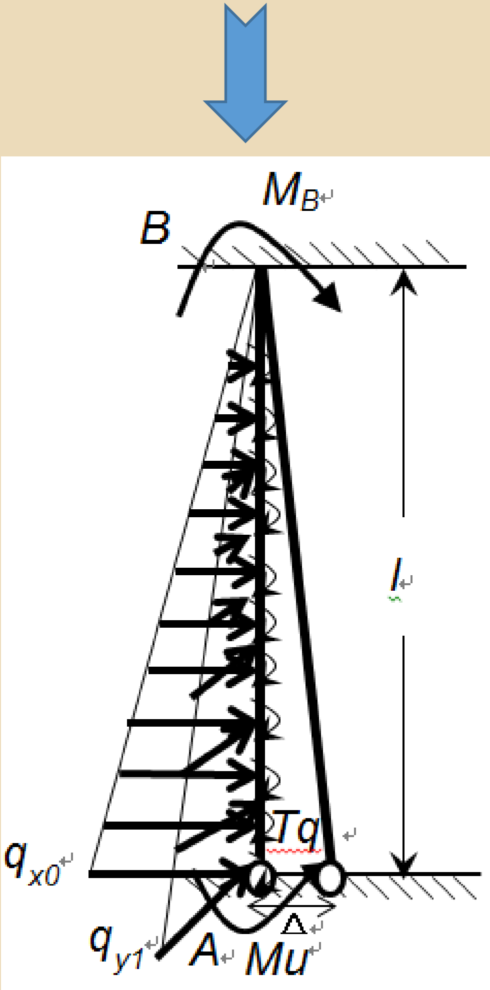
The failure modes of the reinforced concrete column(a) Type I (photo by Pei et al.2011)
(b)Type II (photo by Zeng et al.2014) (c)Type III (photo by Pei et al.2011)

4. Resistance of exposed elements

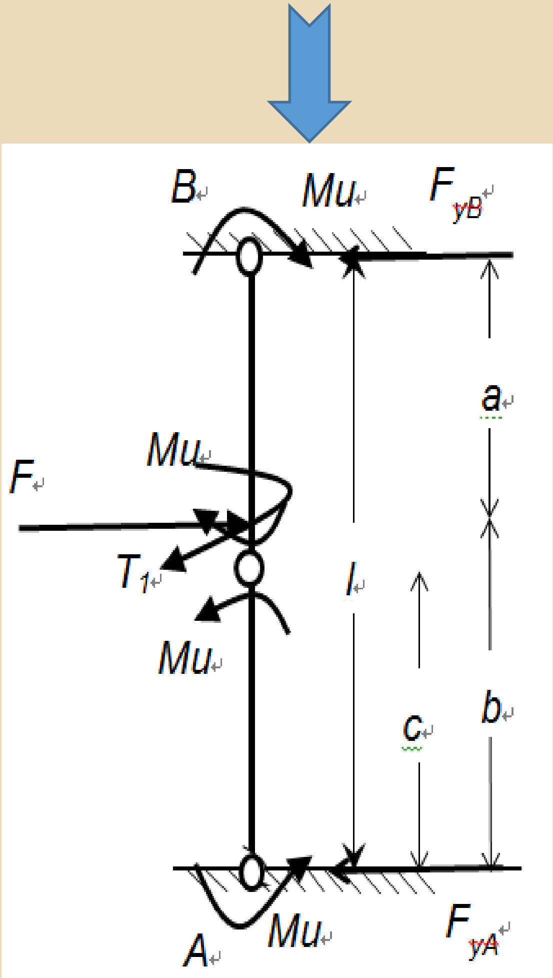
TypeI: One plastic hinge



Type II: Two plastic hinge

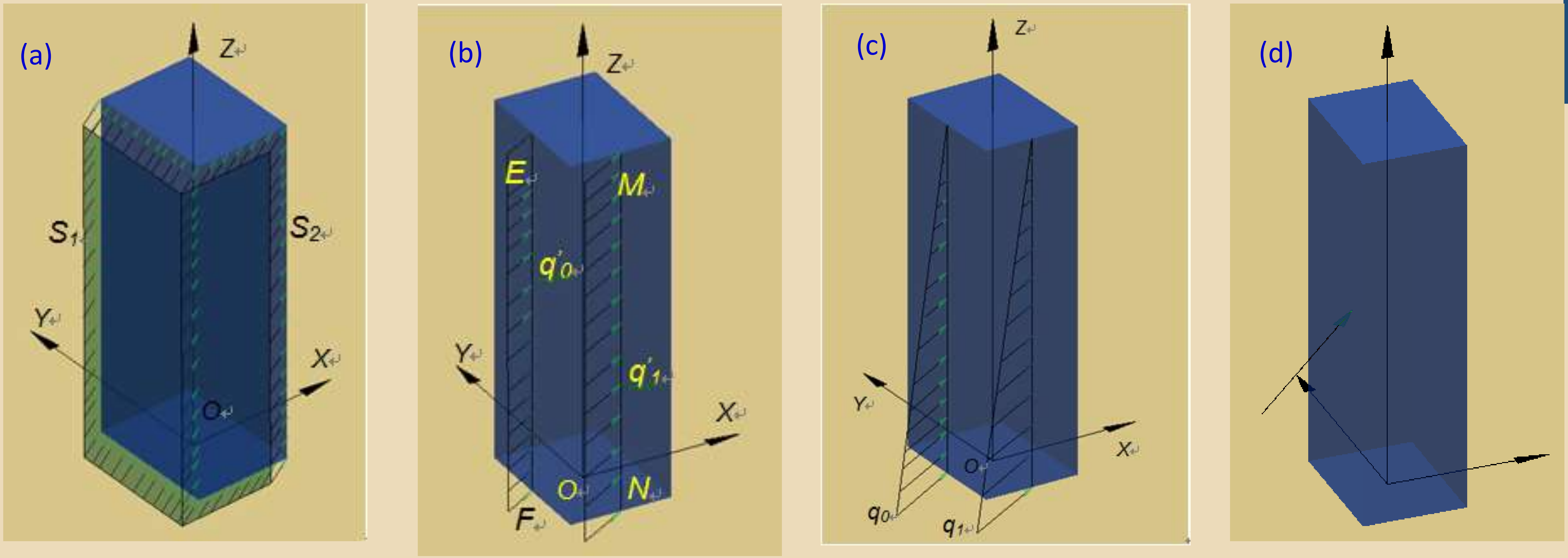


Type III: Three plastic hinge



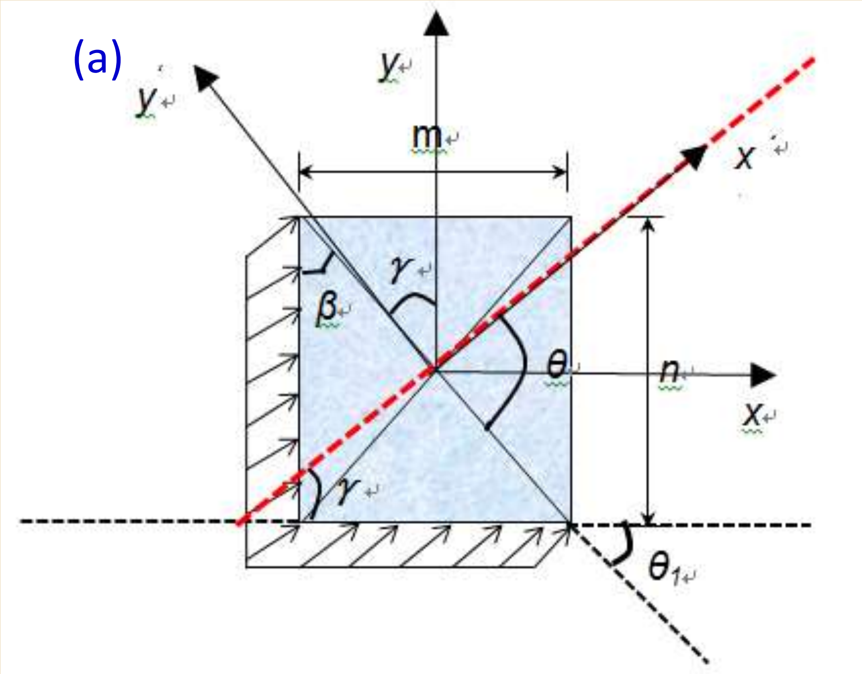
4. Resistance of exposed elements

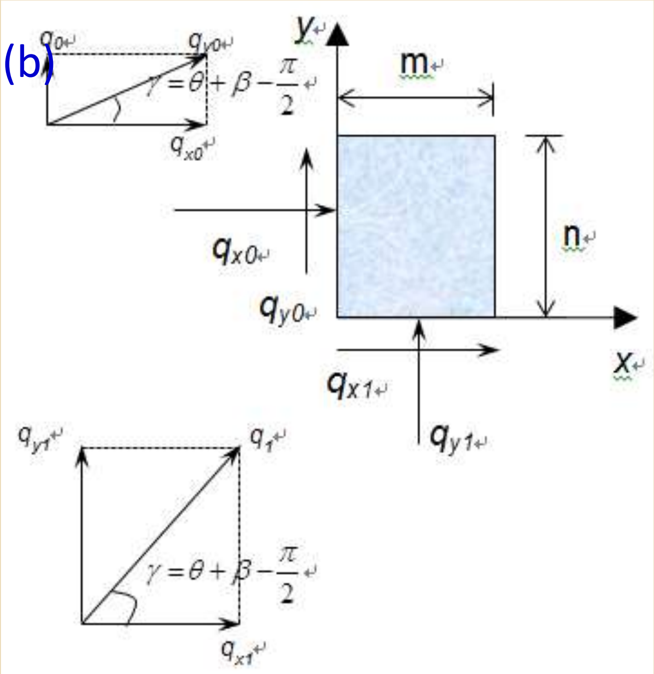
◆The centroid of the 3-dimensional coordinate is in coincidence with the centroid of rectangle. The x-axis is parallel to one side of the rectangle, the y-axis is parallel to the other side of the rectangle and the z-axis is parallel to the side of the column.

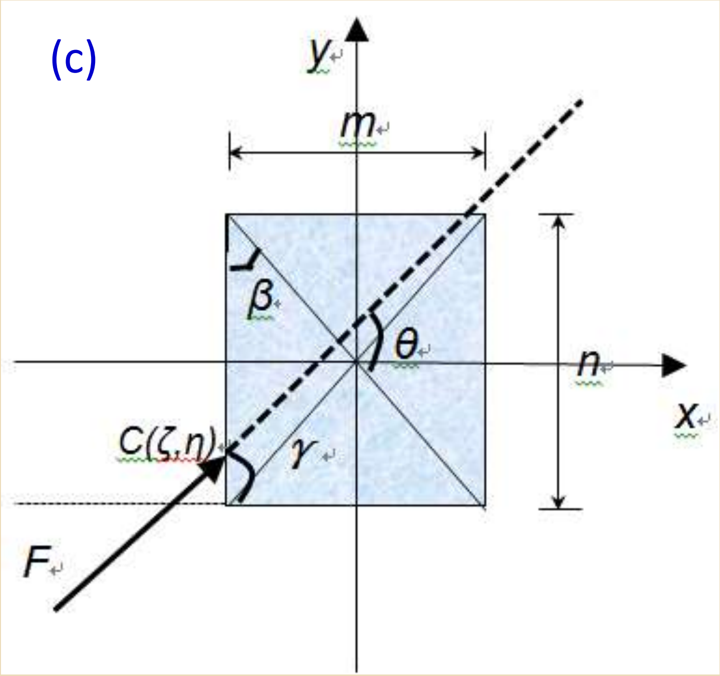


4. Resistance of exposed elements

◆In practice, the first two modes would appear when the sliding body impacted the RC column, while the last mode would occur when the structures subjected to huge rockfall.







4. Resistance of exposed elements

- A hydraulics model was used to calculate the dynamic pressure of sliding body

$$P = \kappa \rho v^2 \cos^2 \theta_1 \tag{28}$$

$$\theta_1 = \frac{\pi}{2} - \beta \tag{29}$$

where θ1 is the smallest angle between the direction normal to the face of the barrier and the flow direction of the sliding body.

- The failure mode of the column is biaxial bending destruction and the bending moment M_A can be determined

$$M_A = \left(\frac{q_{x0} l^2}{20}\right)^2 + \left(\frac{q_{y1} l^2}{20}\right) \tag{30}$$

The maximum value of the triangle distribution on the straight line of *EF* on the plane S_1

The sliding body force of per unit height acting on the straight line of *EF* on the plane S_1

$$q_{x0} = 2k\rho v^2 \cos^2 \theta_1 n \cos\gamma \leftarrow q_0' = 2k\rho v^2 \cos^2 \theta_1 n \tag{31}$$

$$q_{y1} = 2k\rho v^2 \cos^2 \theta_1 m \sin\gamma \leftarrow q_1' = 2k\rho v^2 \cos^2 \theta_1 m \tag{32}$$

The maximum value of the triangle distribution on the straight line of *MN* on the plane S_2

The sliding body force of per unit height acting on the straight line of *MN* on the plane S_2

The critical velocity of sliding body for type I

$$v = \frac{\sqrt{10M_u}}{(cos^2\gamma cos^4\theta_1 k^2 l^4 n^2 \rho^2 + cos^4\theta_1 k^2 l^4 m^2 sin^2\gamma\rho^2)^{\frac{1}{4}}} \tag{33}$$

4. Resistance of exposed elements

◆The horizontal force can be ignored when the longitudinal bars yield at the time of plastic hinge forms. The gravity and the deformation of the column are neglected, so the axial force is not considered.

the critical velocity of sliding body for type II

$$v=\frac{\sqrt{180M_u l^2-360E\Delta I_y'}}{\sqrt{7}l^2(\cos^4\theta_1 k^2 n^2\rho^2\cos^2\gamma+\cos^4\theta_1 k^2 m^2\rho^2\sin^2\gamma)^{\frac{1}{4}}}$$

$$M_B=M_q+M_\Delta+M_b \quad (34)$$

the bending moment at top end of the column

$$M_q=\frac{7}{120}ql^2 \quad (35)$$

the bending moment caused by the horizontal load

$$M_\Delta=\frac{3EI_y'}{l^2}\Delta \quad (36)$$

the bending moment caused by the horizontal displacement

$$M_b=-\frac{M_u}{2} \quad (37)$$

the bending moment caused by the ultimate bending moment

4. Resistance of exposed elements

- According to the elastic collision theory of Hertz

$$p(r) = p_m[1-(\frac{r}{a})^2]^{\frac{1}{2}} \quad (38)$$

$$a = (\frac{3FR}{4E_0})^{\frac{1}{3}} \quad (39)$$

$$E_0 = \frac{E}{1-\nu^2} \quad (40)$$

$$p_m = \frac{3F_0}{2\pi a^2} \quad (41)$$

- Based on the elastic collision theory of Hertz and Johnson

$$\alpha = \frac{a^2}{R} = (\frac{9F^2}{16RE^2})^{\frac{1}{3}} \quad (42)$$

$$F_0 = \frac{4}{3}E\sqrt{R}\alpha^{\frac{3}{2}} \quad (43)$$

- Based on the theory of Yang et all

$$v_y = (\frac{\pi}{2E})^2(\frac{8R^3}{15M})^{\frac{1}{2}}(p_y)^{\frac{5}{2}} \quad (44)$$

$$F^2 = 2Ea_y(Mv^2 - \frac{1}{6}Mv_y^2) \quad (45)$$

$$F = \frac{\sqrt{180E^4Mv^2a_y - \pi^4R^3p_y^5a_y}}{3\sqrt{10}E^{\frac{3}{2}}} \quad (46)$$

- According to the static or kinematic theorem of limit analysis of the failure modes, the balance equation can be listed out.

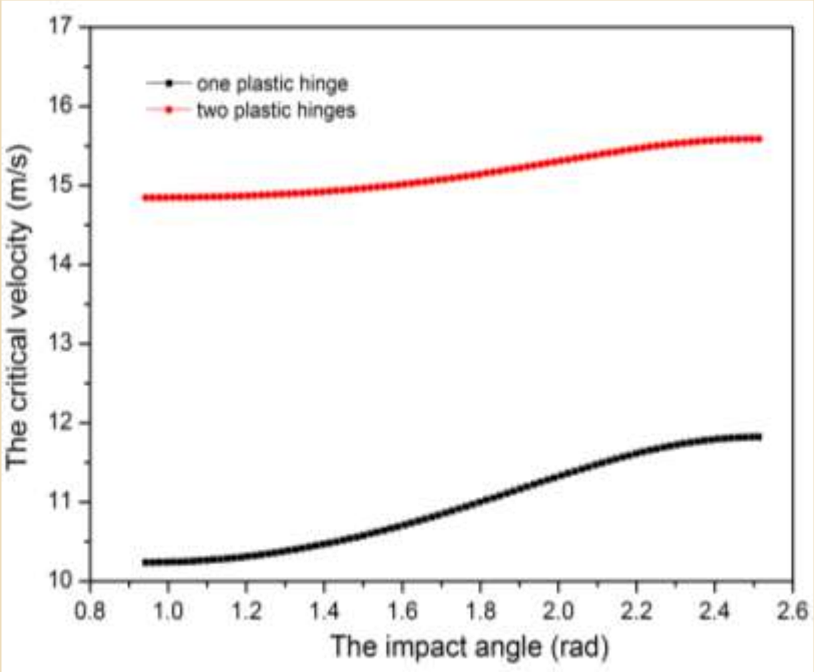
$$\frac{Fb}{l}(l-c) - F(b-c) - 2M_u = 0 \quad (47)$$

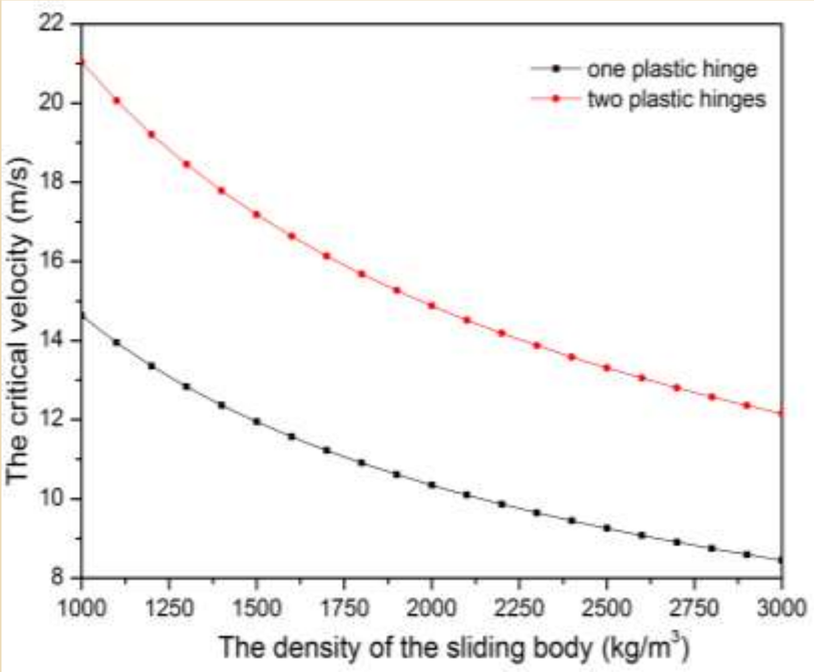
$$v = \frac{\sqrt{360E^3l^2Mu_{u3}^2 + b^2c^2\pi^4R^3a_yp_y^5 - 2blc^2\pi^4R^3a_yp_y^5 + l^2c^2\pi^4R^3a_yp_y^5}}{cE^2\sqrt{180b^2 - 360bl + 180l^2}\sqrt{Ma_y}} \quad (48)$$

the critical velocity of sliding body for type III

4. Resistance of exposed elements

◆ Influence of physical property of the sliding body on failure character

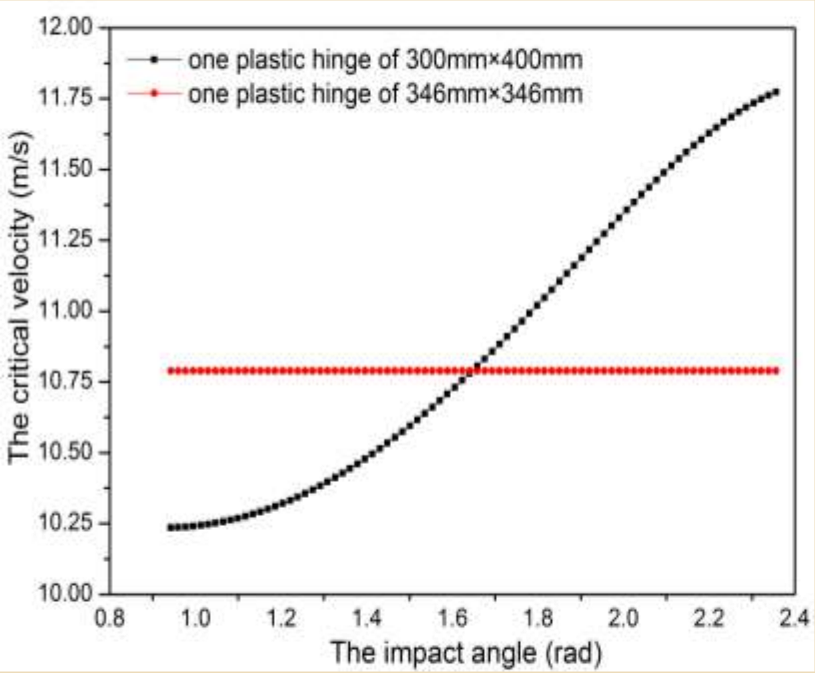


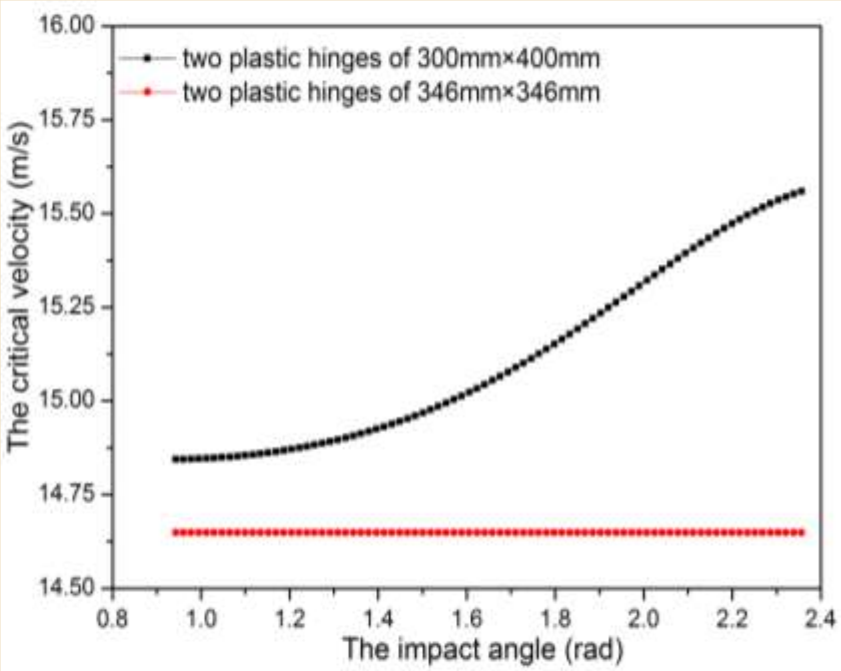


➢As the density of the sliding body increases, the impact velocity of the sliding body may reach its critical value and the failure modes may change from no destruction to one plastic mechanism or more than one hinge.

4. Resistance of exposed elements

◆ Influence of physical property of the sliding body on failure character

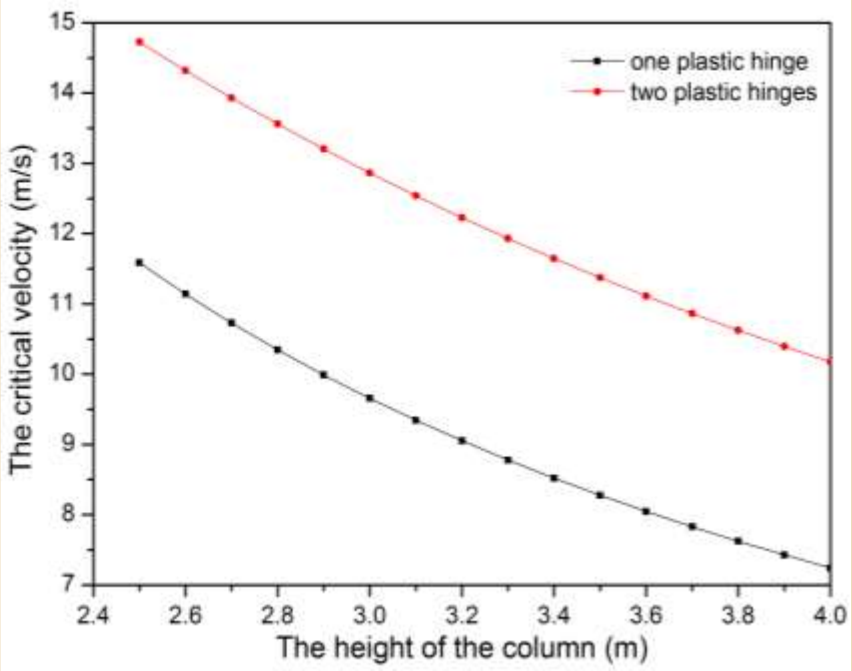


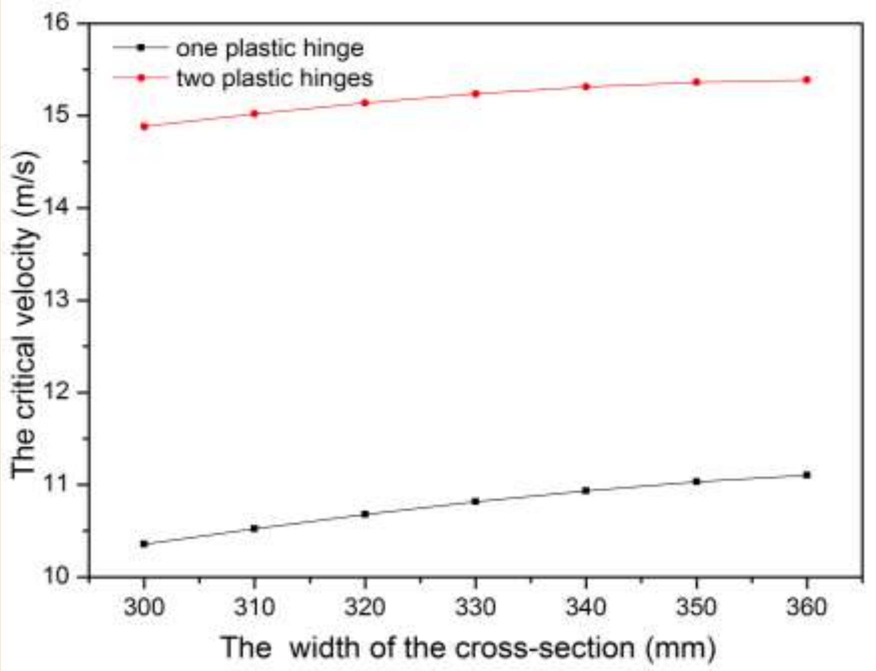


➢ No matter for one plastic hinge destruction and two plastic hinges destruction the critical velocity of the column increases with the increasing of the impact angle for the rectangle cross-section and has a fixed value for the square one.

4. Resistance of exposed elements

◆ Influence of physical property of the RC column on failure character



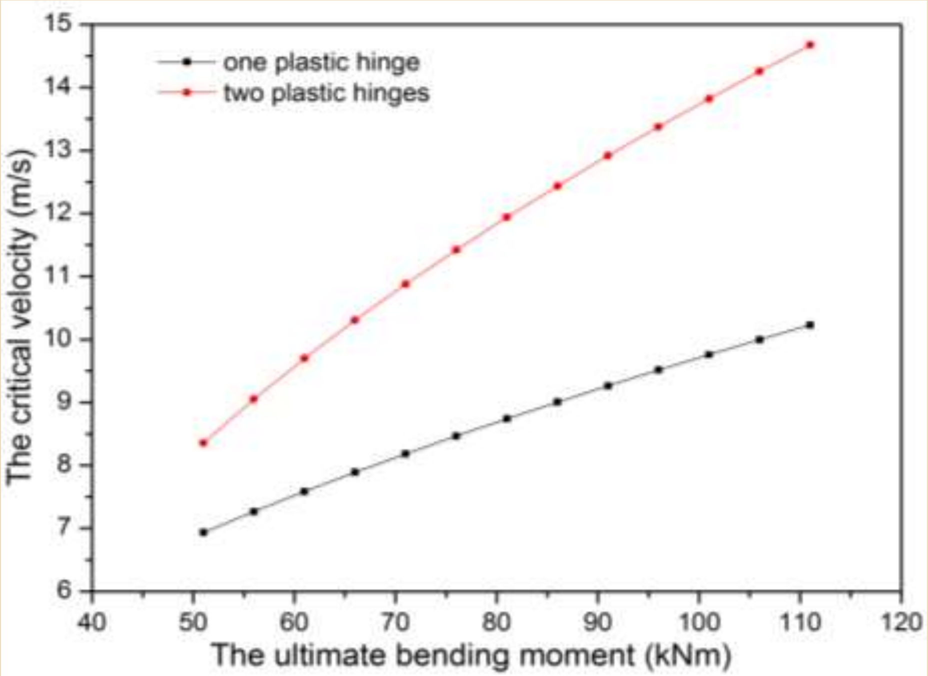


➢When the impact velocity of sliding body remains constant, the height of the column differs in different failure modes.

➢The slenderness ratio of RC column significantly affects the critical velocity of sliding body when the height and the width of the RC column changes.

4. Resistance of exposed elements

◆ Influence of physical property of the RC column on failure character



➢ The critical velocity of the sliding body increases with the increasing of the ultimate bending moment of the column in different failure modes.

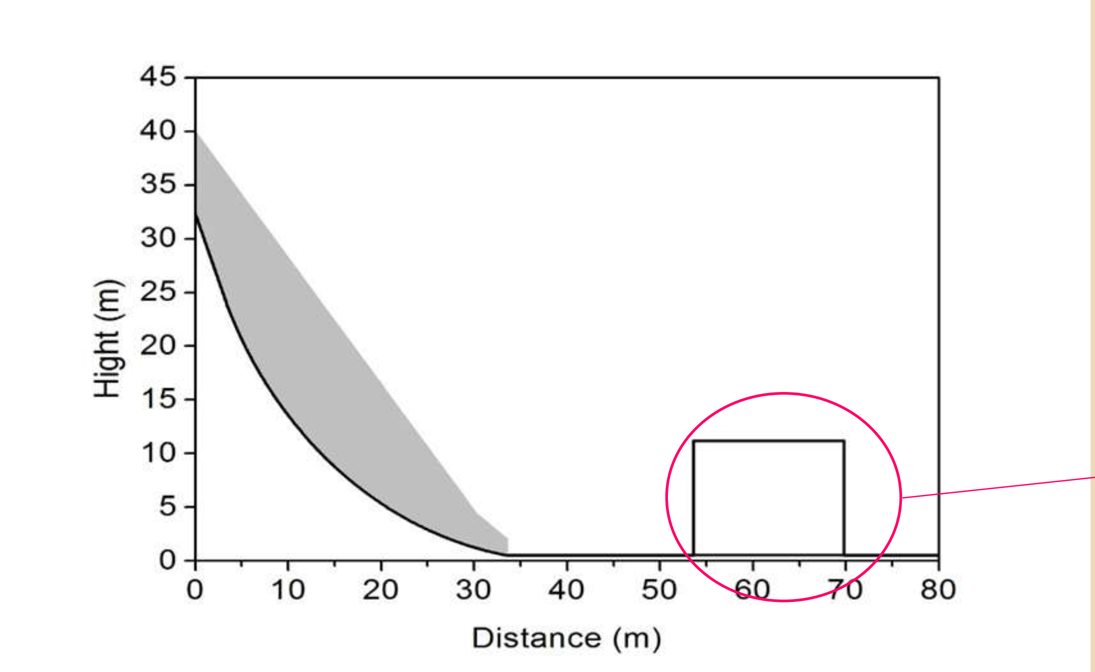
➢ When the impact velocity of sliding body is a fixed value, the column may show different failure modes for different impact direction.

Outline

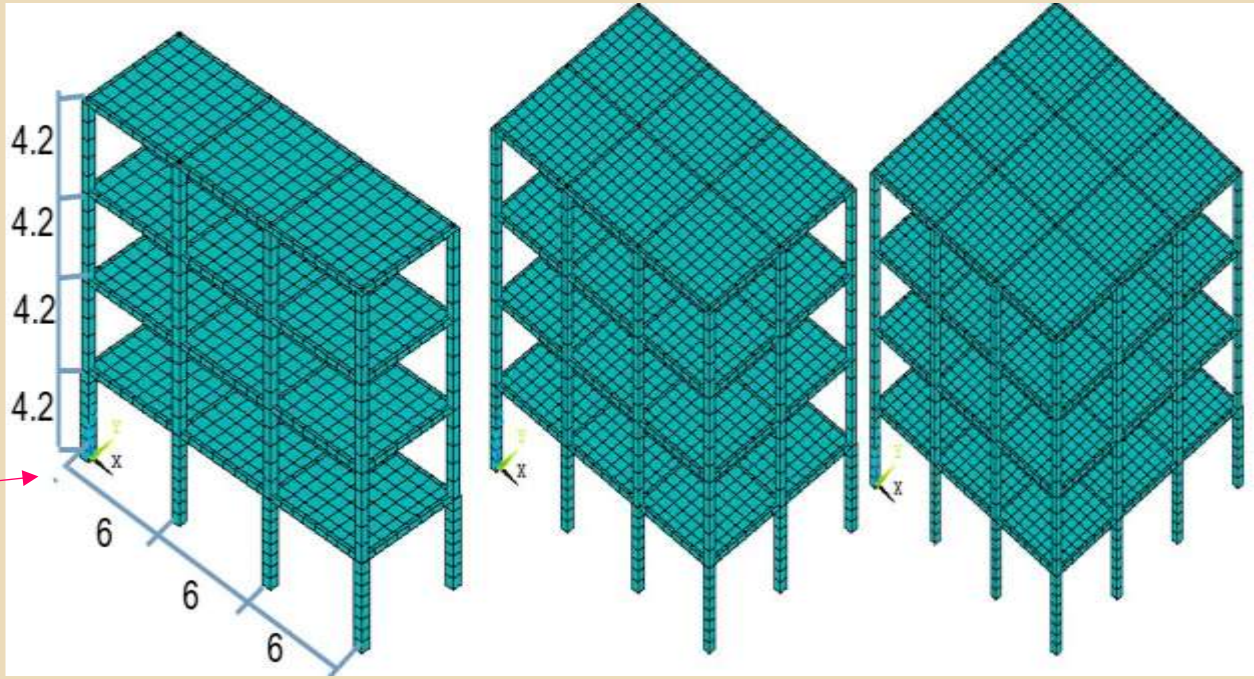
- *Background*
- *Experimental investigation on the spatial distribution of landslide intensity*
- *Runout analysis model for 3D landslide*
- *Resistance of exposed elements*
- ***Case study***
- *Conclusions*

5. Case study

The risk assessment model based on the failure probability of hazard-affected bodies is applied in an example.



Sketch of landslide at the onset of sliding



Geometry model for structure

5. Case study

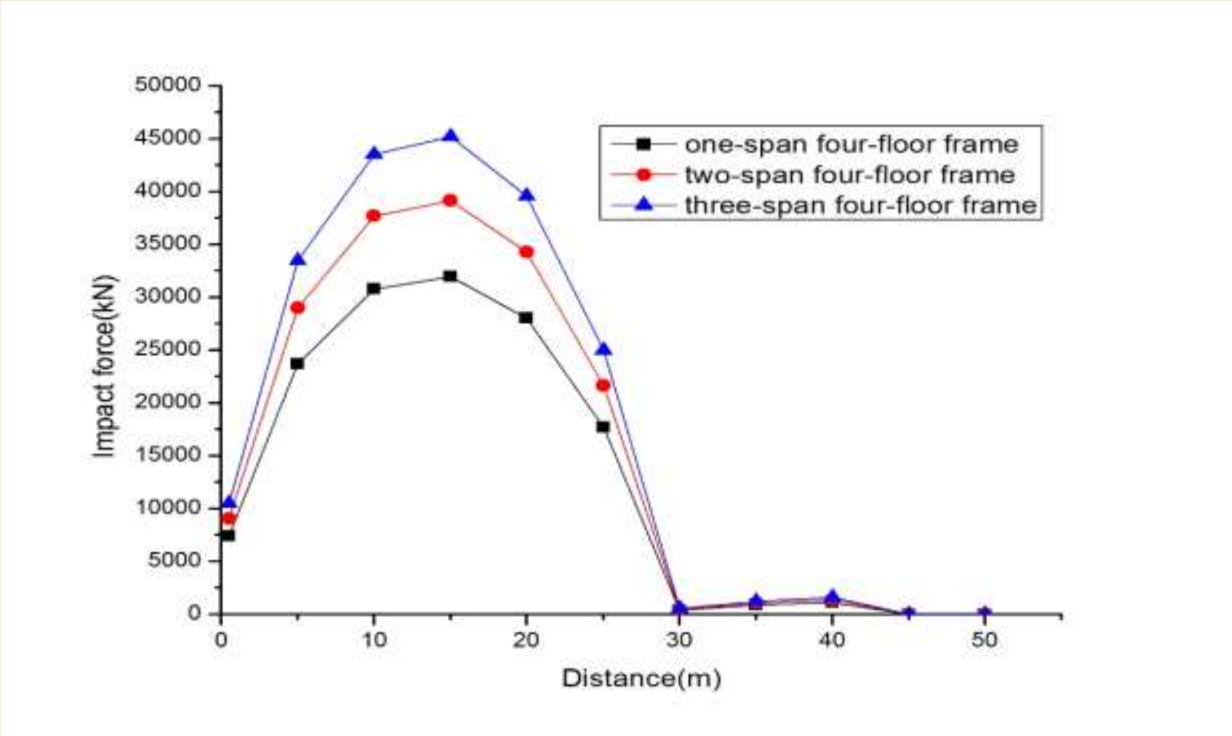
- Here, the risk of landslides is expressed in the form of conditional probability.

$$\mathrm{R} = \mathrm{P(F)} \sum_{i=1}^{n} \{P_i(S|F)V_i(P|S)E_i\}$$

Where, $\mathrm{P(F)}$ and $P_i(S|F)$ describe the possibility of hazard occurrence, $V_i(P|S)$ reflects both the hazard intensity and the hazard resilience of the affected body.

- Traditional risk calculation equation: $\mathrm{R} = P_f \times C$

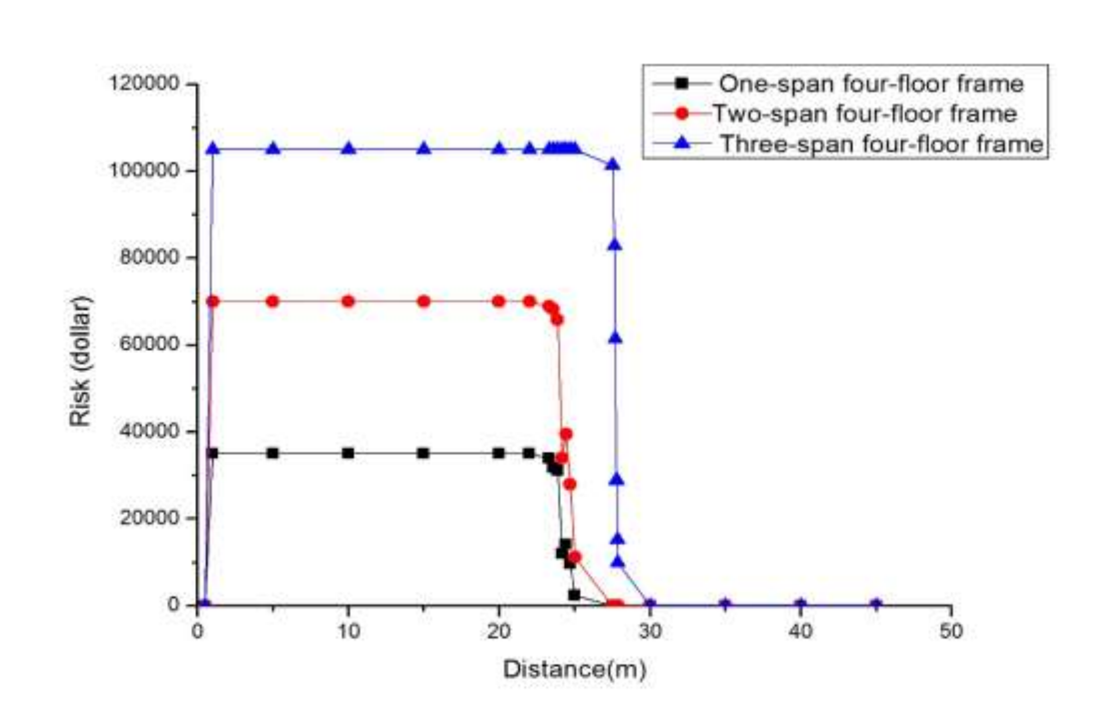
5. Case study

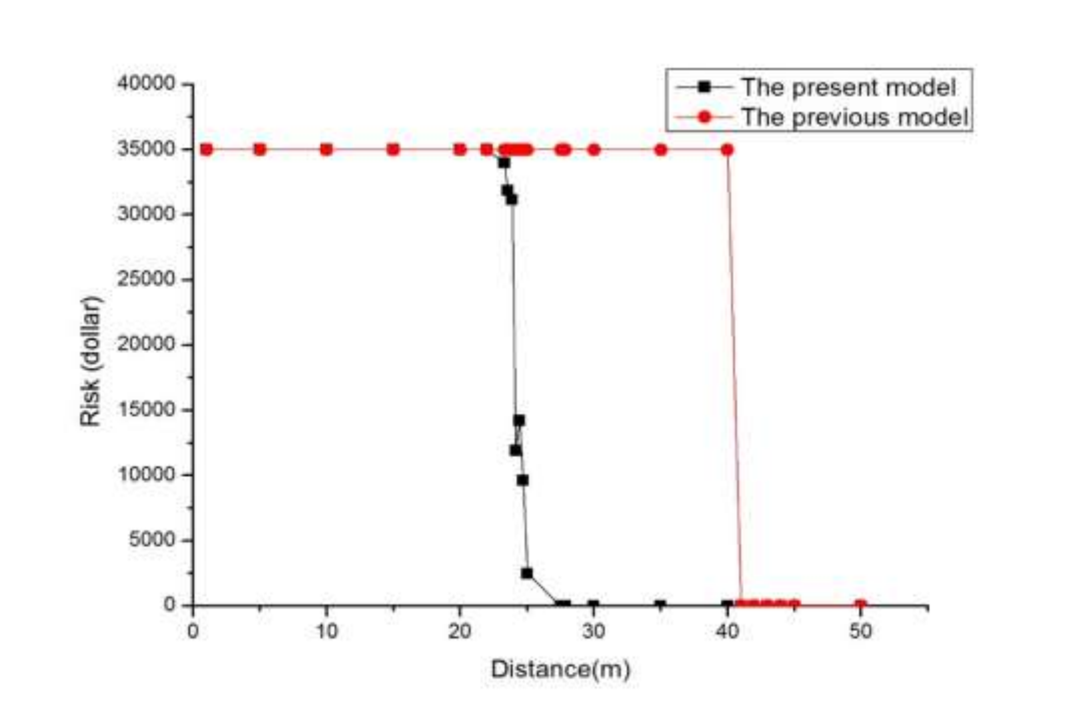


Impact forces of landslide for different type structures

- ➢ The stronger the calamity resistance, the bigger impact force the structure bears.
- ➢ The impact force vary with different failure pattern.

5. Case study

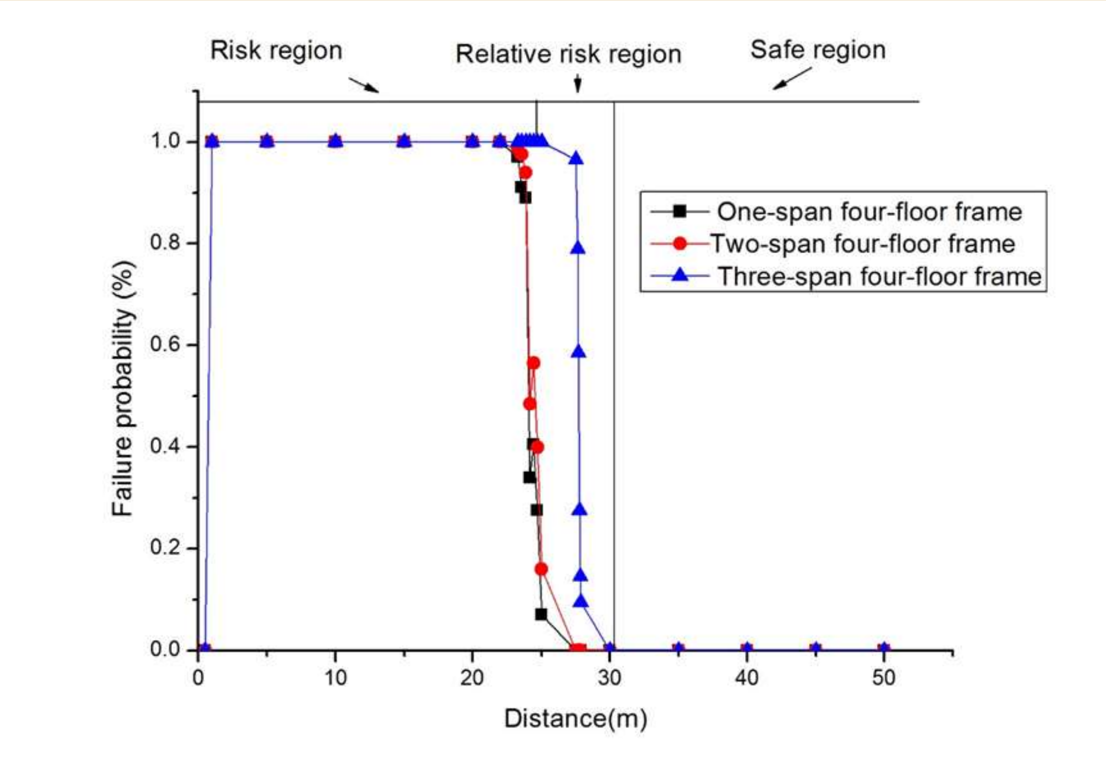




Landslide risk of different structure with the increase of distance

- Under the condition of the same failure probability, the risk of landslide increases with the increase of the quantity and construction cost of hazard-affected bodies.
- The risk is invariable within the hazard range of landslide in the previous model.

5. Case study



Failure probability of different structure with distance

While, three regions which consist of the risk region, relative risk region and safe region can be introduced to describe the degree of safety for the structure.

6.Conclusions

- Experiment investigation on the interaction mechanism between sliding body and building elements are conducted.

- A three-dimensional spring-deformable-block model has been introduced to predict post-failure motion and influence area of landslides .

- Resistance calculation model is proposed to assess the hazard bearing capability of different type of buildings.

Thanks for your attention!

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