

Response to the editor:

Dear editor,

Thank you so much for working on our manuscript this hard pandemic time. Wish you healthy and everything smooth. Since we got the feedback, we worked very hard and revised the manuscript very carefully. The point-by-point response to the reviewers had been attached. Now we response the comments as following:

Comments to the Author:

Based upon the reviewers' comments, the manuscript needs substantial revisions. In detail, a revision of the English language is necessary, since in many parts the text is quite unclear and difficult to understand. Another crucial point is the use of such an approach in other landslide cases, as envisioned by the Authors: this should be better explained, in order to effectively evaluate the possibility in using such approach in other geological and morphological settings.

Authors are kindly invited to read carefully the reviewer's comments and prepare the revised manuscript accordingly.

Response: Thank you for your good comments. We checked the language very carefully. Dhruva Pikha Shrestha is one of the authors, who is the associate professor from ITC with good background of English writing. He has revised the relative sentences which are confusing or difficult to understand. Please see the sentences marked by blue color.

For another crucial point, we have added our explanation in the section of discussion in the manuscript. We specified the applicability of the approach and pointed out its limitation. We agree with you that the results from this study should be verified or tested in other landslide cases. Our research is based on detailed field investigation, monitoring, and analysis in such specific landslides, we think the results should be applicable for the similar geological background areas prone to slow-moving landslides or similar landslide displacement process. We hope the results can be a good supplement for physical vulnerability of landslides. Currently, intensive researches on slow-moving landslides vulnerability in the Three-gorges Reservoir is strengthened, where we are applying our approach for more case studies. We are confident this approach can be verified and modified through our continuing studies. Essentially, the results of physical vulnerability of buildings on slow moving landslides are mostly related to the force of soils acting on building's foundation. Relatively, the quantitative relationship between the physical vulnerability of buildings and landslide displacement process is very weakly studied around the world. It needs more concentration of studies.

Sincerely yours,

Lixia Chen

Point-by-point response to the reviews

Dear Referee 1,

We would like to thank you for your professional and constructive comments concerning our manuscript entitled "Assessment of the physical vulnerability of buildings affected by slow-moving landslides". These comments are all valuable and helpful for revising and improving our manuscript. The main corrections in the manuscript and point-by-point to your comments are as following (the page number and line number in this refer to **the revised manuscript**).

Specific comments:

(1) In Section 2.2.1 the Authors recall the equivalent elastic beam – originally introduced by Burland and Wroth (1974) to define a damage ability criterion – in order to compute the maximum deflection exhibited by the same beam under a uniform load whose modulus equals q . In Figure 2 this uniform load acts horizontally, in correspondence of the lateral surface of the building's foundation affected by the landslide; whereas in Figure 3 the uniform load is applied vertically to the elastic beam. Accordingly, it is not clear in which direction the maximum deflection develops. Furthermore, symbols adopted in Figures 2 and 3 to denote the geometrical characteristics of the building's foundation are not internally consistent. Could the Authors better explain?

Response: thank you very much for the comment. In Figure 3, we actually try to express the uniform load applied horizontally, so sorry for the confusing. We plan to revise the figure 3 as follows.

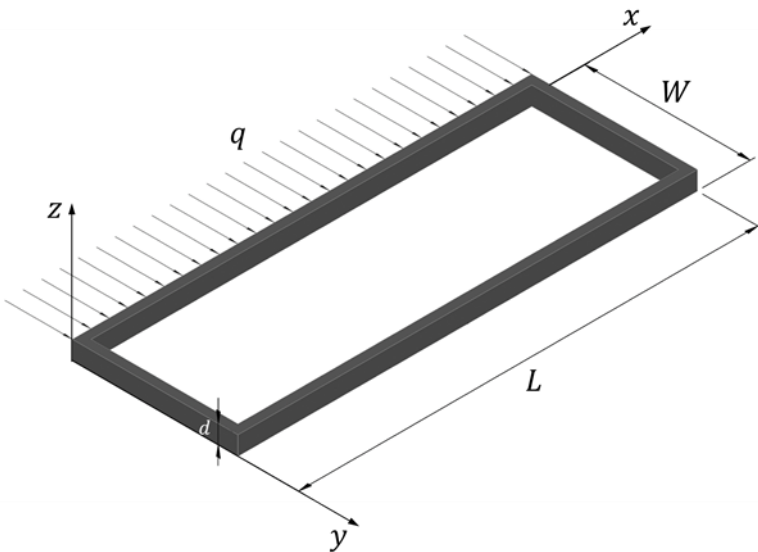


Fig.3. The simple beam with its foundation affected by landslide thrust.

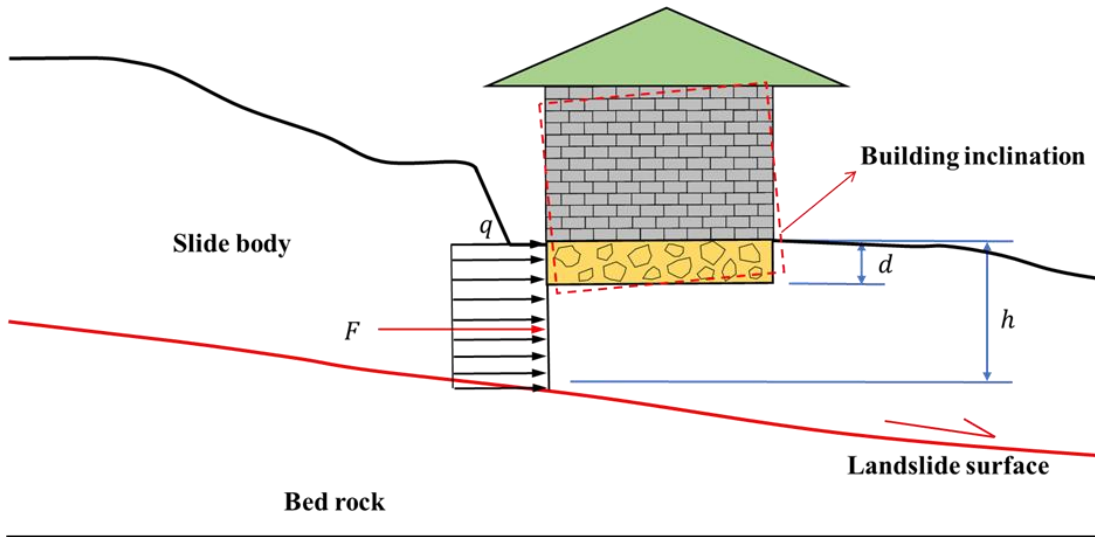


Fig. 2. Schematic diagram of landslide thrust action on a building.

We revised the symbols adopted in Figures 2 and 3 to ensure them consistent. Where q denotes the distribution force on the foundation (kN/m), F denotes the horizontal component of landslide residual thrust (P_i) in Eq. (3), and h denotes the vertical distance from sliding surface to the ground surface. (Fig.2). L , W , and d denote the length, width and depth of the building foundation (Fig.3).

(2) In the same Section 2.2.1 the concept of “inclination” of a building is introduced. Does this inclination corresponds to the “rotation” or “slope” (i.e. the change in gradient of a line joining two reference points of the foundation base) or to the “tilt” (describing the rigid body rotation of the whole superstructure or a well-defined part of it) defined by Burland and Wroth (1974)? Or does it refer to another well-defined parameter? Please clarify. I also suggest to associate the Eq. (9) – used to express mathematically the concept of inclination – with a Figure helpful to better understand the meaning of symbols adopted in Eq. (9), including the angle alpha.

Response: thank you very much for the suggestion. The incline angle of the building is the angle between the vertical plane of inclined building and the vertical plane of the original design building or the angle between the bottom plane of displacement foundation and the horizontal plane of foundation bottom of the original design. The inclination of the building is the tangent value of the incline angle. We add a figure to better understand the meaning the meaning of symbols adopted in Eq. (9) as follow. More explanation has also been put in the context. Please see line 150 to line 166.

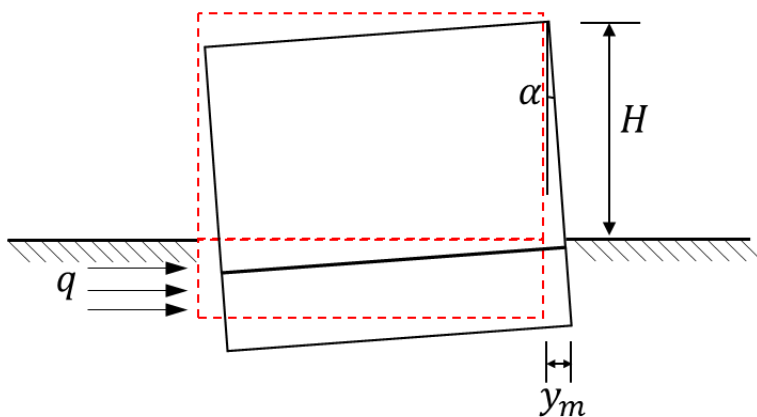


Fig. 4. The inclination of the building

(3) In Table 3 the shear strength parameters of soils involved in the shear zone of the Manjiapo landslide are summarized. Are they residual shear strength values? And, more in general, what type of laboratory tests was carried out? Please explain.

Response: thank you very much for the comment. The shear strength parameters in Table 3 are residual values. According to the report provided by the China Geological Survey (Hunan Institute of Xiangxi Geological Engineering Survey) in 2017, six groups of undisturbed soil samples were collected from the shear zone of the Manjiapo Landslide. Obtained by residual shear tests in the laboratory, the shear strength parameters of slip soils in Table 3 are the average values of these six groups of soil samples. So we added more details about shear strength parameters in line 238 to line 240.

(4) In Table 4 it is not clear if the Young's modulus refers to the masonry constituting the building superstructure or to the material constituting the building foundation. Please clarify.

Responses: Thank you very much for your comments. The Young's modulus in Table 4 refers to the material constituting the building foundation. We will revise Table 4 as follows.

Table 4. Parameters of the case building and its foundation on the Manjiapo landslide

For building			For foundation			Soil depth where the building located (m)	
Length <i>L</i> (m)	Width <i>W</i> (m)	Height <i>H</i> (m)	Depth <i>d</i> (m)	Young's modulus <i>E</i> (MPa)	Shear modulus <i>G</i> (MPa)		<i>E/G</i>
25	9	2.8	1	2250	865	2.6	5

(5) In Section 4.1 the rainfall scenarios considered for transient seepage analyses are introduced. However, relevant information is provided neither on the fixed boundary conditions nor on the adopted hydraulic conductivities. Please improve this Section.

Response: thank you very much for the suggestion. We use the SEEP/W code (GEOSTUDIO) to analyze the groundwater seepage of Manjiapo landslide. We obtain the amount of 3-day cumulative precipitation corresponding to each return period by using PT (Pearson type) III distribution model and the rainfall data (Fig. 12 in the revised manuscript). The average amount of 3-day cumulative precipitation is input to the software in turn, and then the groundwater under the rainfall scenarios is simulated.

The saturated volumetric water content is 0.4 by cutting ring method. The saturated permeability coefficient is obtained by back analysis. We choose the saturated volumetric water content and the permeability coefficient by the variable-controlling approach. Three groups of input values are: 0.4, 0.1; 0.4, 0.2; 0.4, 0.3. Then, the groundwater is simulated and then validated for the rainfall event in March 2018. The root mean square error (RMSE) is utilized to check the accuracy of calculation. Lower RMSE means smaller error and better prediction effect. The results of RMSE are shown in the following table. We find the saturated volumetric water content is 0.4 and the most suitable value of permeability coefficient is 0.3 m/d. We added the detailed analysis in the Section 4.1. Please see line 309 to line 320.

Table 5. Permeability coefficient back analysis of the rainfall event in March 2018, by comparing the root mean square errors (RMSE) of for three hydrological gauges (installed by the authors in December 2017, see Fig.5) on Manjiapo landslide

The permeability coefficient (m/d)	0.1	0.2	0.3
RMSE (STK-1)	2.280	2.222	2.154
RMSE (STK-2)	0.860	0.677	0.615
RMSE (STK-3)	2.540	2.491	2.405

Note: the saturated volumetric water content by Lab test is 0.4.

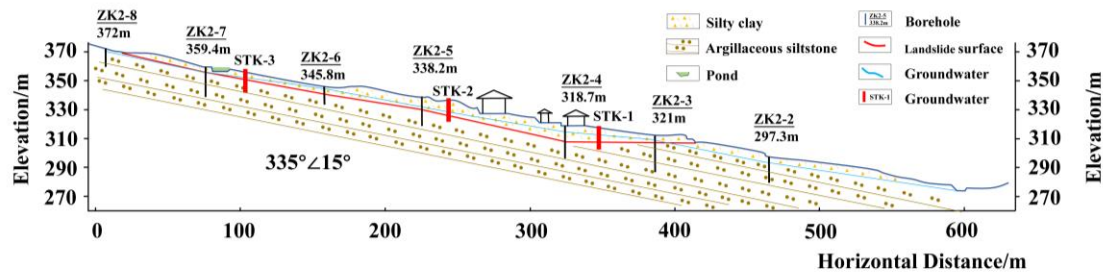


Fig. 6. Geological profile of I-I' of the Manjiapo landslide (1:1 000).

(6) In Table 5 the results obtained for the four considered rainfall scenarios are summarized. In all the cases, the factor of safety (F_s) is lower than 1. This would imply that the landslide is always moving, in disagreement with the information gathered by the Authors about the cracks on the ground surface of the Manjiapo landslide. In particular, the Authors observe that “Meanwhile, since the extreme rainfall events were recently rare, the deformation of the landslide did not obviously change, which was similar to the deformation situation in June 2016. For example, the cracks on the landslide did not expand, and the number of new cracks was very few” (page 10 – lines from 249 to 252). Probably, the shear strength parameters used for the limit equilibrium analyses are too low (see Table 3) and should be compared with those deriving from the back-analysis of the event occurred on June 2016.

Response: thank you very much for the suggestion. The factor of safety (F_s) in the original Table 5 is for the area where the building is located, but not for the whole landslide. This is pointed out by the sentence from line 195 to 197 on page 9. To avoid confusing, we revised this variable to be F_{sb} . In addition, we add the results of safety factors for the whole landslide under four scenarios in table 6 as follows. Now in this table, F_s refers to the factor safety of the whole landslide. From table 6, we find that the landslide is stable with factor of safety 1.457.

Table 6. Landslide residual thrust, pushing force on the building’s foundation, and vulnerability of the building based on four scenarios: (a) dry condition without earthquake, (b) rainfall with a return period of 5 years (3-day precipitation 235 mm/d from Fig. 11), (c) rainfall with a return period of 10 years (3-day precipitation 279 mm/d from Fig. 11) without earthquake, and (d) rainfall with a return period of 50 years (3-day precipitation 352 mm/d from Fig. 11) without earthquakes.

Scenarios	F_{sb}	F_s	F(kN/m)	q (kN/m)	i (%)	V
a	0.853	1.457	142	28	0.053	0.053
b	0.529	0.819	1756	351	0.656	0.656
c	0.481	0.778	2040	408	0.762	0.762
d	0.428	0.632	2638	528	0.985	0.985

Note: F_{sb} is the safety factor of the area where the building is located.

(7) In Section 4.2 the results of the vulnerability analysis concerning a selected building within the affected area of the Manjiapo landslide are presented. Focusing on the obtained vulnerability curve (Fig. 12) the Authors observe that “the physical vulnerability is very low when the landslide is stable with a safety factor greater than 1.0” (lines from 326 to 327). How is this observation justifiable? Indeed, it is expected that the building vulnerability equals 0 (no damage) if the landslide does not move. In this regard, are the Authors sure that the chosen Weibull (1951) function is the best one to mathematically express the vulnerability curve when $1/F_s$ is adopted as landslide intensity parameter?

Response: thank you very much for the comment. For slow-moving landslides, they can have a F_s greater than 1.0 but with cracks within the landslide area. Based on the Chinese standard of Specification of Risk Assessment for Geological Hazard (DZ/T 0286-2015), there are three stability states of landslide according to the range the safety factor (F_s) of landslide as the following table.

Table 7. The range of safety factor (Fs) of landslide and its state (referred to Ministry of Land and Resources of the PRC, 2015)

The safety factor F_s	$F_s \leq 1.00$	$1.00 < F_s \leq F_{st}$	$F_s > F_{st}$
Stability state of landslide	unstable	Less stable	stable
Description	(1) Many newly expanded cracks on the ground and new deformation on buildings and vegetation. (2) Obvious scratch and displacement on the main scarp. (3) Cracks on the crown of landslide.	(1) Local deformation on the ground. (2) No obvious deformation on the main scarp. (3) No obvious expansion of the cracks on the buildings. (4) Small cracks on the crown of landslide.	(1) No sustained deformation on the ground. (2) No crack expansion on the landslide. And no new deformation on buildings and vegetation on the landslide. (3) No scratch and obvious displacement on the main scarp.

Note: $F_s \neq 0$. And F_{st} denotes the design safety factor which is defined according to the slope safety level and slope type.

When the whole landslide has F_s value from 1.0 to F_{st} (the design safety factor of the Manjiapo landslide is 1.30), the landslide will have small scale deformation or cracks. While the buildings located across the cracks can have damages with a certain degree.

In the Three Gorges Reservoir area, China (Chen et al., 2016) and other areas, such as Moio della Civitella (Salerno province, Italy) (Infante et al., 2016), the buildings on the huge, slow-moving landslides will appear this state. So, to solve the problem on building's vulnerability, we need to focus on the local stability of this kind of landslide like Manjiapo landslide, but not the whole body. In Figure 13, the F_s value is for the local stability of the soil where the case building located. Following the above question, we need to modify F_s in Figure 13 to be F_{sb} . We can find from Figure 13 and Figure 16 that, when $1.0 < F_{sb} < 1.30$, the building vulnerability is from 0 to 0.1. This means the building is damaged very slightly, which is consistent with the real state of buildings on slow-moving landslides.

In this regard, we are sure that Weibull function is suitable to express the vulnerability curve. In fact, Weibull function is used to express the vulnerability curve in many present literatures and has high acceptance, such as Dario Peduto et al. (2017), Kang et al. (2016), Papathoma-Köhle (2016), Negulescu et al. (2010). We add the literatures in line 201 to 202.

Reference

- Chen, L., Cao, X., Yin, K., Wu, Y., and Li, Y.: Physical vulnerability assessment for buildings impacted by a slow moving landslide based on field work and statistical modelling, in: Landslides and Engineered Slopes. Experience, Theory and Practice, 2016.
- Infante, D., Confuorto, P., Di Martire, D., Ramondini, M. and Calcaterra, D.: Use of DInSAR Data for Multi-level Vulnerability Assessment of Urban Settings Affected by Slow-moving and Intermittent Landslides, *Procedia Engineering*, 158, 470–475, doi:10.1016/j.proeng.2016.08.474, 2016.
- Peduto, D., Ferlisi, S., Nicodemo, G., Reale, D., Pisciotta, G., and Gullà, G.: Empirical fragility and vulnerability curves for buildings exposed to slow-moving landslides at medium and large scales, *Landslides*, doi:10.1007/s10346-017-0826-7, 2017.
- Kang, H. sub and Kim, Y. tae: The physical vulnerability of different types of building structure to debris flow events, *Natural Hazards*, 80(3), 1475–1493, doi:10.1007/s11069-015-2032-z, 2016.
- Papathoma-Köhle, M.: Vulnerability curves vs. Vulnerability indicators: Application of an indicator-based methodology for debris-flow hazards, *Natural Hazards and Earth System Sciences*, doi:10.5194/nhess-16-1771-2016, 2016.
- Negulescu, C. and Foerster, E.: Parametric studies and quantitative assessment of the vulnerability of a RC frame building exposed to differential settlements, *Nat. Hazards Earth Syst. Sci.*, 10(9), 1781–1792, 2010.

(8) In the Discussion, the Authors stress that “the physical vulnerability is inversely proportional to the building height” (line 384). This is not in agreement with thresholds values of the building inclination summarized in Table 2. Indeed, as the building height (from the outdoor ground) increases the threshold value decreases.

Response: thank you very much for the comment. Table 2 expresses threshold values of the building inclination for three types of buildings with different height. In this manuscript, we focus on the first class of building with height lower than 24 m, which are common residential buildings in rural areas of China. As to this kind of building, the threshold is a fixed value 1%. Meanwhile, we use the vertical height of tilted building calculated from the outdoor ground to calculate the inclination of the case study building. Please see line 155 to 163. To avoid confusion, we will remove the parameter of the building height (from the outdoor ground) and don't make sensitivity analysis of the building height. We reselected some parameters to do sensitivity analysis. Please see line 376 to 378 and Figure 14 and 15.

Table 2. The threshold value of building inclination (Ministry of Housing and Urban–Rural Development of PRC, 2016).

Height H_g (m)	$H_g \leq 24$	$24 < H_g \leq 60$	$60 < H_g \leq 100$
Threshold value i_m	1%	0.7%	0.5%

Here, H_g denotes the building height which is calculated from the outdoor ground.

(9) In my opinion, the vulnerability curves shown in Figure 15 have to be further validated before applying them in analyses at regional scale (lines from 403 to 408).

Response: thank you very much for the good comment. We are currently doing the researches on regional scale slow-moving landslide risk assessment in the Three Gorges reservoir area, China, which involves regional scale vulnerability assessment for buildings. We totally agree with you that before applying the results from this manuscript, we will do further validation. We rewritten the content in line 435 to 451.

Technical corrections:

(1) The symbol adopted throughout the manuscript to indicate the unit of measurement of force should be “kN” (lowercase k) instead of “KN”.

Response: thank you very much for the good suggestion. We have modified “KN” to be “kN” in the revised manuscript.

(2) The symbol adopted in Table 3 to indicate the unit of measurement of stress should be “kPa” instead of “kpa”.

Response: thank you very much for the good suggestion. We have modified “kpa” to be “kPa” in the revised manuscript.

(3) In the Note of Table 3 it is not clear if the information provided about the “permeability coefficient” and the “volume of water content” (or “volumetric water content”?) refers to the considered soil in saturated conditions or not. Relevant units of measurement should be provided, if applicable.

Response: thank you very much for the good suggestion. In the Note of Table 3, the information provided about the permeability coefficient and the volumetric water content refers to the considered soil in saturated conditions. The saturated volumetric water content is 0.4 by cutting ring method. The saturated permeability coefficient is obtained by back analysis. We find that the most suitable value of permeability coefficient is 0.3 m/d. We will add the detailed analysis in the Section 4.1.

Please see line 309 to line 320.

We tried our best to improve the manuscript and made some changes in the manuscript. We feel great thanks for your professional review work on our article, and hope that the correction and response will meet with approval.

Sincerely,

Lixia Chen

Dear Referee 2,

Thank you very much for your professional comments on our manuscript. These comments are all valuable and helpful for revising and improving our manuscript. The main corrections in the manuscript and the point-by-point responses to your comments are as following (the page number and line number in this letter refer to **the revised manuscript**):

Specific Comments:

(1) the Abstract should be rearranged and totally rewritten. It cannot be a list of steps followed during the analysis. Authors should mention the problem and the approach followed to get the results.

Response: Thank you for your good comments. We have rearranged and rewritten the abstract, which mentioned the problem and the approach followed to get the results. Please see line 11 to 26.

(2) Fig.3, pag.6. Authors should better clarify, for instance with an additional Figure, how the lateral forces impacting the foundation can be associated with y_m (that is the inflection under vertical loads). At the moment the concept of i_m is not clear.

Response: Thank you for your good comments. Figure 3 on page 6 did not clearly express the direction of lateral forces impacting the foundation. We try to express the uniform load applied horizontally, so sorry for the confusing. We will modify this figure as follows.

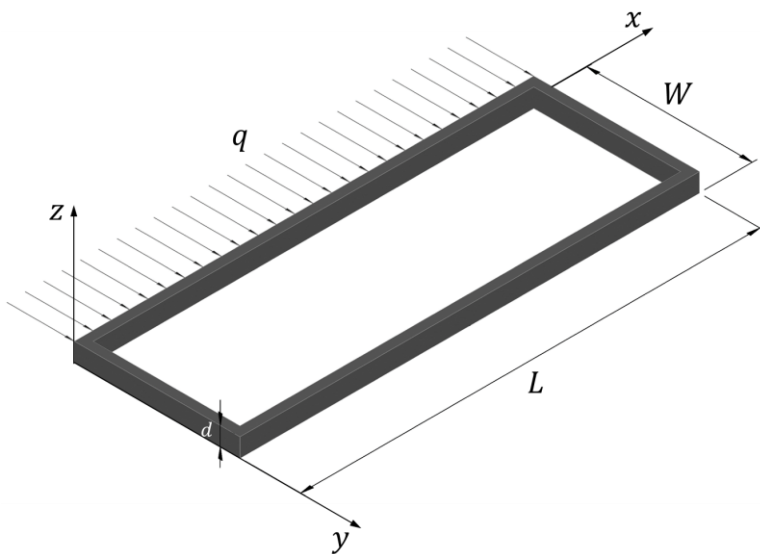


Fig.3. The simple beam with its foundation affected by landslide thrust.

The concept of i_m is the threshold value of inclination of buildings. Buildings with inclination exceeding i_m are dangerous and uninhabitable. In Table 2, we listed out the standard of threshold values for three kinds of buildings with different height. Please see line 183 to 184.

(3)The sentence (pag.7) referring to Finno et al. (2005) should be better clarified.

Response: Thank you for your good comments. The original sentence is: Since cracks on walls are not visible, especially when the building with high stiffness is exceedingly inclined because of the ground deformation, they usually serve as the indicators of damage degree evaluation if the building stiffness is small (Finno et al., 2005)

Sorry for the confused expression in the above sentence. We want to clarify that cracks on building walls are not the only indicator to assess vulnerability, especially when the building has a very good stiffness. So, we revised this sentence as follows.

Finno et al. (2005) reported that when highly stiff buildings are very inclined due to ground deformation, the wall cracking phenomenon is not obvious. On the contrary, if the stiffness of the building is lower, the cracking on the wall becomes serious. This research shows that using only cracks as an indicator is not suitable for vulnerability assessment. Other indicators, such as inclination, should also be taken into consideration. We revised the English sentence in line 175 to 180.

(4) The Authors identify the damage classification with vulnerability. This aspect deserves further clarifications based on widely shared literature.

Response: Thank you for your good comments. In order to simplify the research work, many researchers directly use damage degree as vulnerability. Tarbotton et al. (2015) defined empirical vulnerability functions as “a continuous curve associating the intensity of the hazard (X-axis) to the damage response of a building (Y-axis)”. Kang et al. (2016) think that the range of damage to the buildings makes it possible to assess the vulnerability using a vulnerability curve that relates the intensity of debris flow with the degree of damage. They use the degree of damage to the buildings to estimate vulnerability. We added the literature in line 172 to 173.

Reference

1. Tarbotton, C., Dall'osso, F., Dominey-Howes, D., Goff, J. The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: comparative review and summary of best practice. *Earth Sci. Rev.* 142, 120–134, doi.org/10.1016/j.earscirev.2015.01.002, 2015.
2. Kang, H. sub and Kim, Y. ta: The physical vulnerability of different types of building structure to debris flow events, *Natural Hazards*, 80(3), 1475–1493, doi:10.1007/s11069-015-2032-z, 2016.

(5) Provide more details on laboratory tests used to gather the values of the shear strength parameters shown in Table 3.

Response: Thank you for your good comments. The shear strength parameters in Table 3 are residual values. According to the report provided by the China Geological Survey (Hunan Institute of Xiangxi Geological Engineering Survey) in 2017, six groups of undisturbed soil samples were collected from the shear zone of the Manjiapo Landslide. Obtained by residual shear tests in the laboratory, the shear strength parameters of slip soils in Table 3 are the average values of these six groups of soil samples. So we added more details about shear strength parameters in line 238 to line 240.

(6) In Figure 12, it is not clear the range of variation of $1/F_s$. Some further comments would be helpful.

Response: thank you very much for the suggestion. Based on the Chinese standard of *Specification of Risk Assessment for Geological Hazard* (DZ/T 0286-2015), there are three stability states of landslide according to the range the safety factor (F_s) of landslide. Please see more details in the following table.

Table 7. The range of safety factor (F_s) of landslide and its state (referred to Ministry of Land and Resources of the PRC, 2015)

The safety factor F_s	$F_s \leq 1.00$	$1.00 < F_s \leq F_{st}$	$F_s > F_{st}$
Stability state of landslide	unstable	Less stable	stable
Description	(1) Many newly expanded	(1) Local deformation on the	(1) No sustained deformation on

cracks on the ground and new deformation on buildings and vegetation. (2) Obvious scratch and displacement on the main scarp. (3) Cracks on the crown of landslide.	ground. (2) No obvious deformation on the main scarp. (3) No obvious expansion of the cracks on the buildings. (4) Small cracks on the crown of landslide.	the ground. (2) No crack expansion on the landslide. And no new deformation on buildings and vegetation on the landslide. (3) No scratch and obvious displacement on the main scarp.
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Note: $F_s \neq 0$. F_{st} denotes the design safety factor.

The value of F_{st} is defined according to the slope safety level and slope type (Table 8). Meanwhile the slope safety level is defined based on the potential economic loss and element at risk. According to the field investigation, there are 116 residents in the affected area of the Manjiapo landslide, and the road passes through the middle part of the landslide. In case of geologic hazard, it will threaten the lives and property of 116 residents and damage more than 67,000 square meters of the land. At the same time, the road will be damaged, threatening the safety of the pedestrians and passing vehicles. The potential economic loss will be more than CNY 5 million. the safety level of the Manjiapo landslide is judged to be second level based on below table.

Table 8. The value of the design safety factor (referred to Ministry of Housing and Urban–Rural Development of PRC, 2013)

the slope safety level		First level	Second level	Third Level
Permanent slope	General condition	1.35	1.30	1.25
	Earthquake condition	1.15	1.10	1.05
Temporary slope		1.25	1.20	1.15

Table 9. The slope safety level (referred to General Administration of Quality Supervision, Inspection and Quarantine of the PRC,2016)

the slope safety level		First level	Second level	Third Level
potential economic loss (CNY)		≥ 50 million	5 million to 50 million	< 5 million
Element at risk	population	≥ 500	100 to 500	< 100
	Infrastructure	Very important	Important	less important

Note: If one of the conditions is met, it will be judged to be the corresponding slope safety level.

So, when the safety factory of the Manjiapo Landslide is greater than 1.30, the landslide is stable and the landslide intensity is very low. In addition, the resistance ability of the building can prevent the building from being destroyed by the low intensity of the landslide (Du, 2013). In summary, the physical vulnerability of the building on Manjiapo landslide is very low when the safety factory is greater than 1.30. It provides that the physical vulnerability of the building on Manjiapo landslide is 0 when the reciprocal value of the safety factor is 0.5. The physical vulnerability of the case study building on Manjiapo landslide is demonstrated in Fig. 13. We add more details to explain the range of variation of $1/F_s$. in line 344 to 365.

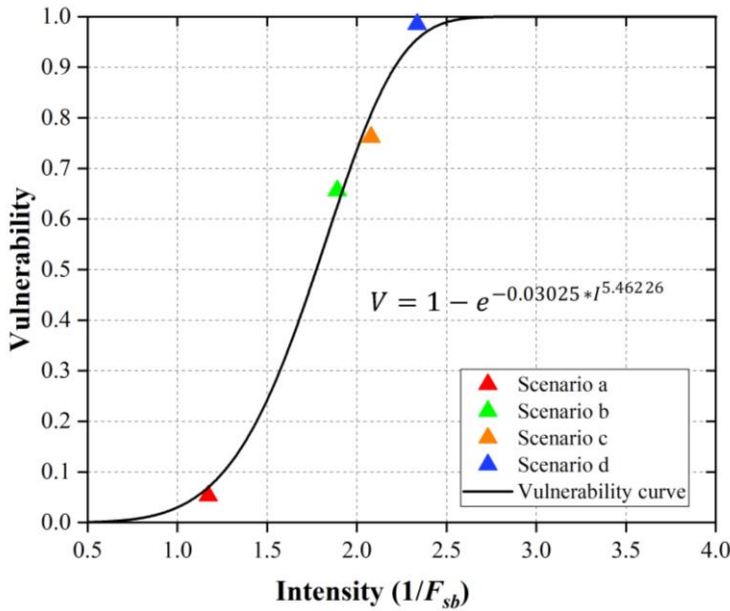


Fig. 13. The physical vulnerability curve for masonry buildings impacted by the slow-moving landslides.

(7) The comparison shown in Figure 13 is unclear. What is there on x-axis?

Response: thank you very much for the comment. By putting these parameters together on a single diagram, we can clearly compare and find out which parameter is more sensitive to vulnerability. We modified the figure. In the new figure, the X-axis stands for the variability rate of the parameter.

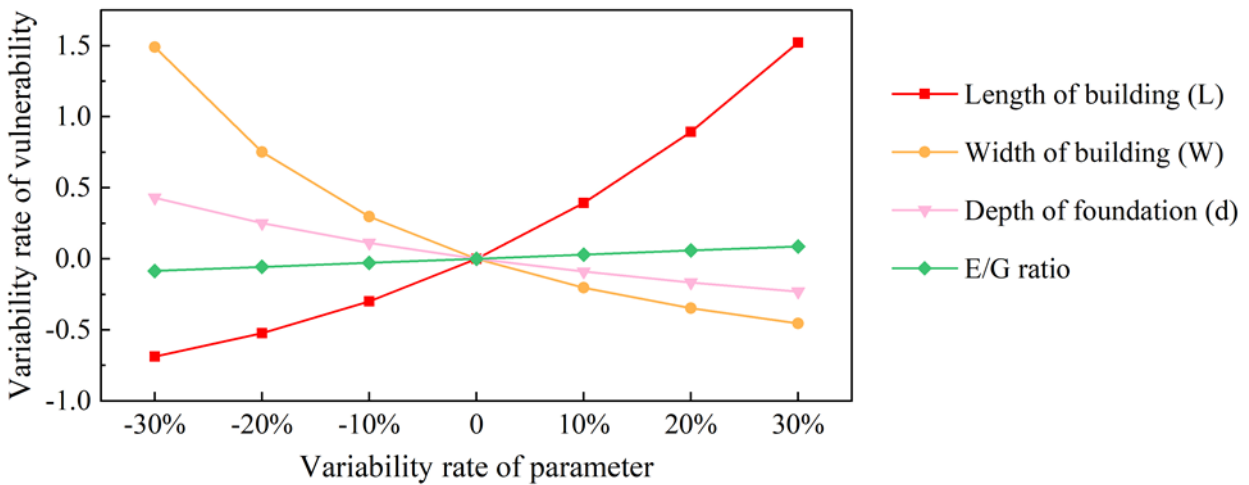


Fig. 15. The sensitivity analysis of building parameters for physical vulnerability.

We can find that the length of the building has the most significant influence on the physical vulnerability of building and the width of the building is the second major factor. So, we modify the figure 16 to show the physical vulnerability curves of building with different length and width. We modified the content in line 375 to 378 and line 389 to 390 and line 403 to 408 and Table 10.

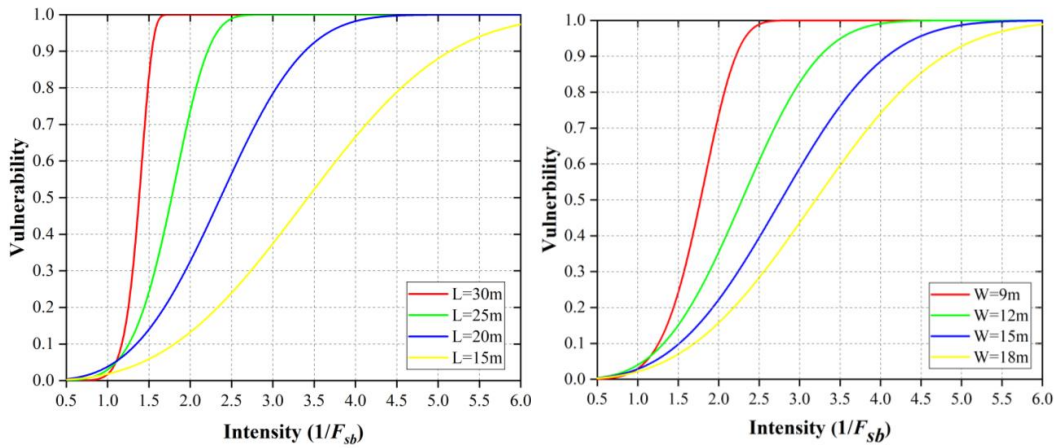


Fig. 16. Physical vulnerability curves of buildings with different parameters: (a) length and (b) width.

(8) Conclusions: please clarify better or add references concerning the calculation of F_S just in correspondence of buildings and over large areas. - Exportability should be better supported with clarifications.

Response: thank you very much for the suggestion. We are currently doing the researches on regional scale slow-moving landslide risk assessment in the Three Gorges reservoir area, China, which involves regional scale vulnerability assessment for buildings. The topic in this manuscript is partially new. There are rare references presently concerning F_S of slow-moving landslides and vulnerability of buildings. But the researches about calculation of F_S over large areas can be found from some researches, such as Muntohar AS, Liao HJ (2009), Apip, Takara K, Yamashiki Y, et al (2010), Salciarini (2006) and Sorbino (2010). We are eager to link the intensity of slow-moving landslides with vulnerability of buildings over large areas. Before applying the results from this manuscript, we will do further validation. We revised some content in discussion and conclusions. Please see line 435 to 453 and line 461 to 467.

Reference

1. Muntohar AS, Liao HJ.: Analysis of rainfall-induced infinite slope failure during typhoon using a hydrological-geotechnical model. *Environ Geol* 56:1145–1159, 2009
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We tried our best to improve the manuscript and made changes in the manuscript. We feel great thanks for your professional review work on our article, and hope that the responses will meet with approval.

Sincerely,
Lixia Chen

Assessment of the physical vulnerability of buildings affected by slow-moving landslides

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Abstract: Physical vulnerability is a challenging and fundamental issue in landslide risk assessment. The previous studies mostly focus on generalized vulnerability assessment from landslides or other types of slope failures, such as debris flow and rock fall, while the long-term damages induced by slow-moving landslides are usually ignored. In this study, a method was proposed to construct physical vulnerability curves for masonry buildings by taking Manjiapo landslide as an example. Landslide force acting on the buildings' foundation is calculated by applying landslide residual thrust calculation method. Considering four rainfall scenarios, the buildings' physical responses from the thrust are simulated in terms of potential inclination by using the Timoshenko's deep beam theory. By assuming landslide safety factor as landslide intensity and inclination ratio as vulnerability, a physical vulnerability curve is fitted and the relative function is constructed by applying a Weibull distribution function. To investigate the effects of buildings' parameters that influence vulnerabilities, the length, width, height, foundation depth, and Young's modulus of the foundation are analysed. The validation results on the case building show that the physical vulnerability function can give a good result in accordance with the investigation in the field. The results demonstrate that the building length, width, and foundation depth are the three most critical factors that affect physical vulnerability value. Also, the result shows that the higher the ratio of length to width of the building, the more serious is the damage to the building. Similarly, the shallower the foundation depth, the more serious will be the damage. We hope that the established physical vulnerability curves can serve as tools for the quantitative risk assessment of slow-moving landslides.

Keywords: slow-moving landslides; physical vulnerability; building; vulnerability curves; risk

1 Introduction

Physical vulnerability is a fundamental and indispensable item in the risk definition presented by Varnes (1984). It can be defined as the degree of loss to a given element or set of elements within an area affected by a hazard (UNDRO, 1984). Physical vulnerability is measured on a continuous scale ranging from 0 (no loss) to 1 (total loss). For quantifying physical loss, such as the structural damage, the physical vulnerability of the elements at risk can be achieved by assessing the damage degree, resulting from the occurrence of a landslide of a given type and intensity (Van Westen et al., 2006).

Recently, physical vulnerability is still a challenge, and there has been a growing interest in quantifying risk due to natural hazards (Van Westen et al., 2006). To quickly and easily analyze the physical vulnerability, researchers have developed various types of tools or software such as HAZUS-MH (FEMA, 2003), RiskScape (King and Bell, 2005), ARMAGEDOM (Sedan et al., 2013), and CAPRA (<https://ecapra.org/>). HAZUS-MH (FEMA, 2003) is considered to be the initially introduced and the most popularly applied software. RiskScape is a national-scale multi-hazard impact model in New Zealand, and ARMAGEDOM is a tool for seismic risk assessment that has three different precision levels (regional territorial scale, district-scale, and the district-scale with more detailed hazard description and physical vulnerability estimation). The majority of the software is employed to analyze the physical vulnerability of earthquakes or multi-hazards, and very few can be utilized for landslide hazard assessment. To solve this problem, Papathoma–Köhle et al. (2015) developed an integrated toolbox designed for buildings subjected to landslides.

In the past decades, researchers have worked on landslide physical vulnerability assessments techniques, which can be grouped into four main approaches as follows: expert judgment (Sterlacchini et al., 2007; Winter et al., 2014; Godfrey et al., 2015; Guillard–Goncalves et al., 2016), statistical (Ciurean et al., 2013; Ciurean et al., 2017), mechanics-based (Luna et al., 2014; Liang and Xiong, 2019; Nicodemo et al., 2020), and integrated (Li et al., 2010; Uzielli et al., 2015b). The results of these approaches include matrices, indicators, and fragility, or physical vulnerability curves or functions. For example, by utilizing the procedures motivated by the seismic risk analysis, Negulescu and Foerster (2010) introduced a simplified methodology to evaluate the mechanical performances of buildings subjected to landslide hazards. Also, Totschnig et al. (2011) presented physical vulnerability curves for debris flow and torrent hazards. Wu et al. (2011) constructed physical vulnerability curves for landslides by considering the landslides' impact energy and impact impulse as the intensity indicators. By utilizing FLO-2D (a hydrologic and hydraulic modeling software of debris flow propagation), Luna et al. (2014) discussed the physical vulnerability functions of buildings at debris flow risk. Based on the physical vulnerability assessments proposed by Li et al. (2010), Uzielli et al. (2015b) modified the method by integrating the assessment of landslide intensity and buildings resilience. Papathoma–Köhle (2015) related hazard intensity (debris-flow depth) with the loss of buildings' damage to buildings' physical vulnerability curves. Soldato et al. (2017) studied the empirical physical vulnerability curves for buildings by considering the

debris-flow depth, the flow velocity, and the impact pressure. Mavrouli et al. (2017) quantified the masonry-buildings' damage induced by rockfalls by calculating the impact force of falling rocks on masonry buildings.

60 The slow-moving landslides are particular types of landslides with slow velocity based on the [classification](#) provided by Cruden and Varnes (1996). Slow-moving landslides on the pre-existing sliding surfaces can cause differential settlement or tilt on structures. People are not usually endangered but damage to buildings and infrastructures may be high (Douglas, 2007). Slow-moving landslides are observed worldwide in many countries, e.g., Italy (Cascini et al., 2008; Antronico et al., 2015; Uzielli et al., 2015a; Nicodemo et al., 2017; Borrelli et al., 2018; Ferlisi et al., 2019), Canada (Clifton et al., 1986; Brooker and
65 Peck, 1993; Moore et al., 2006; Barlow, 2000), China (Chen et al., 2016; Zhang et al., 2018; Dong et al., 2018; Wang et al., 2018), USA (Esser, 2000), and Australia (Jworchan et al., 2008).

Fell et al. (2008) [suggested the estimation of the](#) physical vulnerability of elements at risk for various landslide types. [The slow-moving landslides may cause partial damage to buildings due to local displacement. The assessment methods for the physical vulnerability of slow-moving landslides are still limited. The aforementioned approaches are not very suitable since](#)
70 [slow-moving landslides have different intensity indicators and different types of damages as compared to that from debris flows, rockfalls, or fast-moving landslides.](#)

The [performance](#) analysis of buildings during the landslide and the inventory of the observed damage is a feasible methodology (Faella and Nigro, 2003). To investigate the physical vulnerability of the buildings impacted by landslides, numerous studies have been conducted regarding the acquisition of landslide deformation displacement or finding the
75 statistical relation between the damage degree of buildings and landslide intensity (Mansour et al., 2011; Abdulwahid and Pradhan, 2017; Nicodemo et al., 2017; Peduto et al., 2017; Chen et al., 2016; Peduto et al., 2018). For example, Mansour et al. (2011) investigated the [relationship](#) between the movement and the expected extent of damage to urban settlements. Based on the persistent scatterer interferometry, Lu et al. (2014) obtained the slow-moving landslides velocity for estimating buildings' economic risk with a total affected area of more than 800 km². Ferlisi et al. (2015) reported that combining the differential
80 interferometry (DInSAR) data and the results of supplementary damage surveys on the slow-moving landslides allowed the preliminary generation of a (maximum velocity) cause-effect (damage) relation. Peduto et al. (2017) applied landslide deformation (cumulative surface displacement and differential settlement) as the input variables to construct the empirical fragility and physical vulnerability curves for buildings. By applying the horizontal strains and angular distortions to the numerical model, Infante et al. (2016) generated physical vulnerability for buildings. Nicodemo et al. (2020) employed the
85 equivalent frame method to analyze the damage of a representative building in case of a slow-moving landslide by numerical modeling. [However, a detailed study on the physical vulnerability of buildings using mechanical analysis is not yet available.](#)

This study proposes a method for assessing the physical vulnerability from the perspective of mechanics and obtains its changes during the process of slow-moving landslides. We first calculate the thrust force of landslide acting on the buildings' foundation and then analyze the buildings' physical response. Multi-scenarios were applied to help in constructing the physical vulnerability curves. After the validation by utilizing an application on a typical building impacted by slow-moving landslides, a sensitivity analysis was conducted on the parameters of the building and its foundation.

2 Proposed method

2.1 Force acting on the building foundation during the landslide process

To quantitatively evaluate the building's physical vulnerability during the landslide process, it is essential to calculate the force acting on the building's foundation. In this study, landslide residual thrust force is calculated by employing the residual thrust method, which is extensively applied in China for slope stability analysis (Nie et al., 2004). A slide-mass is divided into different slices in this method and a force analysis is performed on each slice. In this way, it is possible to easily obtain the thrust of a landslide by utilizing the arbitrary shape of the sliding surface and under complex loads. The landslide residual force can be calculated by applying Eq. (1)–(6). In this method the groundwater seepage should be considered under rainy conditions, which can be performed using the SEEP/W code (GEOSTUDIO). The physical vulnerability curve is estimated using landslide safety factor to express the strength of landslide. Landslides with smaller safety factors are more unstable, resulting in greater residual thrust on the building's foundation.

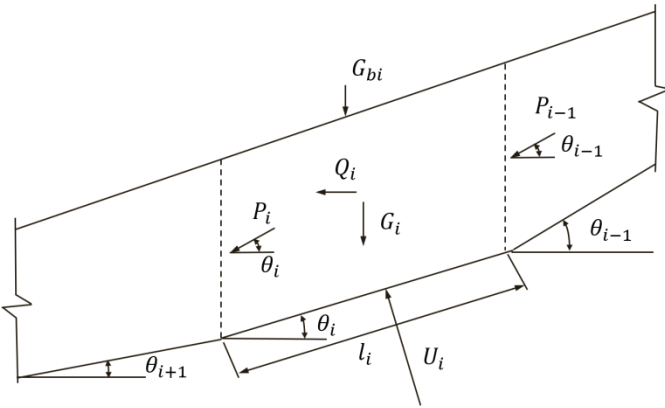


Fig. 1. Computing model of residual thrust method with a broken-line slip surface (Ministry of Housing and Urban-Rural Development of PRC, 2013).

The safety factor of landslide, F_s , is defined based on Chinese code of *Technical Code for Building Slope Engineering* (GB 50330-2013) as follows:

$$F_s = \frac{\sum_{i=1}^{n-1} (R_i \prod_{j=1}^{n-1} \psi_j) + R_n}{\sum_{i=1}^{n-1} (T_i \prod_{j=1}^{n-1} \psi_j) + T_n} \quad (1)$$

For a single slice, the residual thrust force of the i th slice is given as follows:

$$P_i = P_{i-1} \times \psi_{i-1} + T_i - R_i/F_s, \quad (2)$$

$$F_i = P_i \times \cos\theta_i, \quad (3)$$

$$R_i = [(G_i + G_{bi})\sin\theta_i - Q_i\sin\theta_i - U_i] \times \tan\varphi_i + c_i l_i, \quad (4)$$

$$T_i = (G_i + G_{bi}) \times \sin\theta_i + Q_i \times \cos\theta_i, \quad (5)$$

$$\psi_{i-1} = \cos(\theta_{i-1} - \theta_i) - \sin(\theta_{i-1} - \theta_i)\tan\varphi_i/F_s, \quad (6)$$

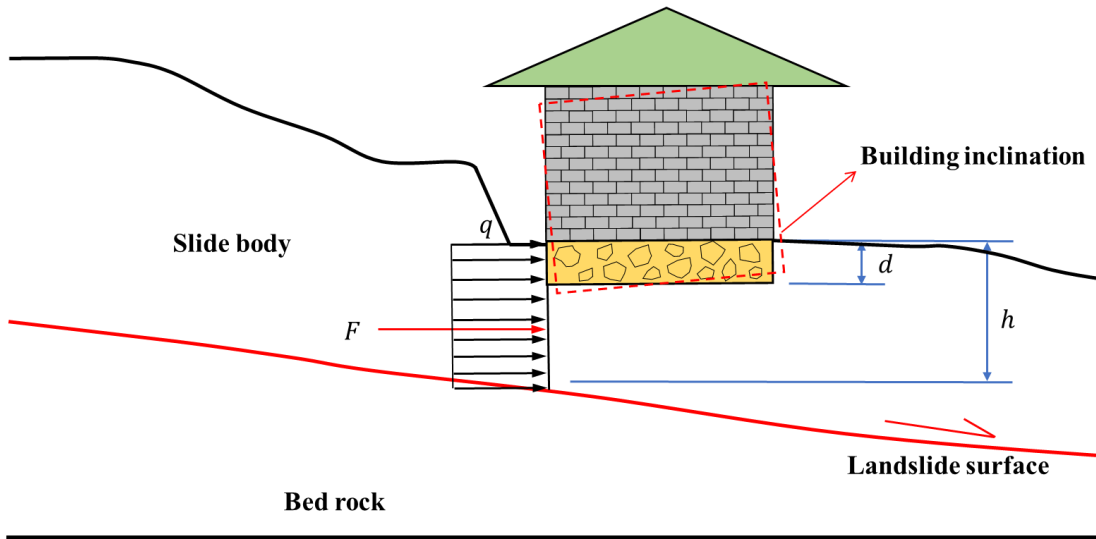
where R_i denotes the resistance force of i th slice (kN/m), T_i denotes the driving force of i th slice (kN/m), P_i denotes the residual thrust of i th slice (kN/m), ψ_i denotes the transmitting coefficient of i th slice, G_i denotes the weight of i th slice (kN/m), G_{bi} denotes the accessional vertical load of i th slice (kN/m), θ_i denotes the angle between the sliding surface and horizontal plane of the i th slice, l_i denotes the length of i th slice (m), c_i denotes the cohesion of i th slice (kPa), φ_i denotes the internal friction angle of i th slice, U_i denotes the pore water pressure of i th slice (kN/m), Q_i denotes the horizontal seismic force of i th slice, and F_i denotes the horizontal component of landslide thrust (shown in Fig. 2).

The transformation of landslide residual thrust force on buildings' foundation depends on the distribution of force. According to Chinese standard (China Railway Second Survey and Design Institute, 1983) and Dai (2002), landslide thrust distribution is approximately assumed to be triangular, rectangular, or parabola shapes, based on the type of sliding mass materials. Each type of thrust distribution corresponds to a distribution function (Table 1).

Table 1. Distribution functions of landslide thrust for various sliding mass materials of the landslide.

Soil types	Distribution form (referred to China Railway Second Survey and Design Institute (1983))	Distribution functions (Referred to Dai(2002))
Clay, Soil-rock, Rock	Rectangle or parallelogram	$q(z) = \frac{F}{d}$
Sand	Triangle	$q(z) = \frac{2F}{d^2}z$
Between clay and sand	Parabola shape	$q(z) = \frac{1.8F}{d^2}z + \frac{F}{10d}$

Note: F denotes the horizontal component of landslide residual thrust (P_i) in Eq. (3), and h denotes the vertical distance from the sliding surface to the ground surface (Fig. 2).



130 Fig. 2. A schematic diagram of landslide thrust action on a building.

2.2 Physical response of buildings

2.2.1 Inclination of buildings

The foundation of the masonry building affected by the landslide thrust can be simplified as a beam (Fig. 3). It has been observed that real structures are normally very complicated, but the simplification of the beam helps in illustrating several important features (Burland, 1974).

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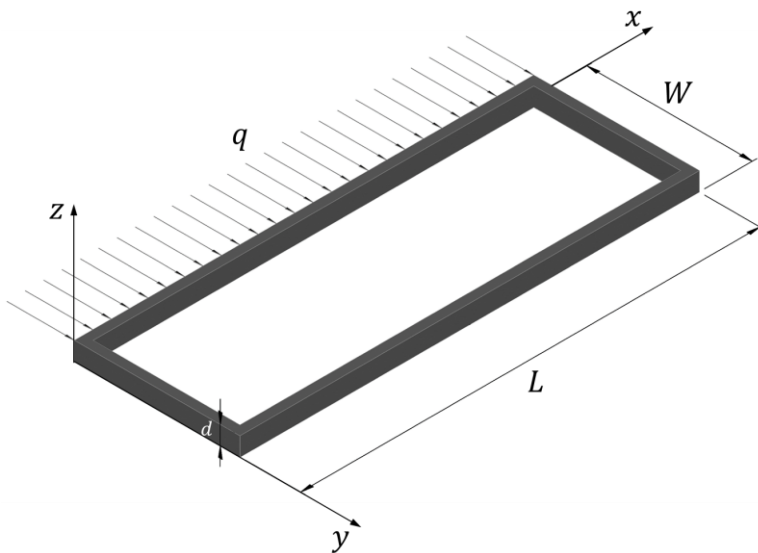


Fig. 3. The simple beam with its foundation affected by landslide thrust.

For illustrative purposes, we only consider the case of a beam with a uniform load. Timoshenko (1984) gave the function of deflection for the uniform loaded beam of unit thickness flexing in both shear and bending as follows:

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$$y(x) = \frac{qx}{24EI} \left(\frac{x}{L}\right) \left(\frac{x^3}{L^3} - 2\frac{x^2}{L^3} + 1\right) + \frac{3qL^2}{4GA} \left(\frac{x}{L}\right) \left(1 - \frac{x}{L}\right), \quad (7)$$

where q denotes the distribution force on the foundation (kN/m), L denotes the length of the building, I denotes the moment of inertia defined by $I = \frac{dW^3}{12}$, in which d denotes the depth of the foundation, and W denotes the width of the building. Also, E and G denote Young's modulus and shear modulus of the foundation materials, respectively.

145 When $= \frac{L}{2}$, the equation for the total central deflection is the following:

$$y_m = \frac{5qL^4}{384EI} + \frac{3qL^2}{16GA}, \quad (8)$$

where the maximum deformation of the foundation is denoted by y_m .

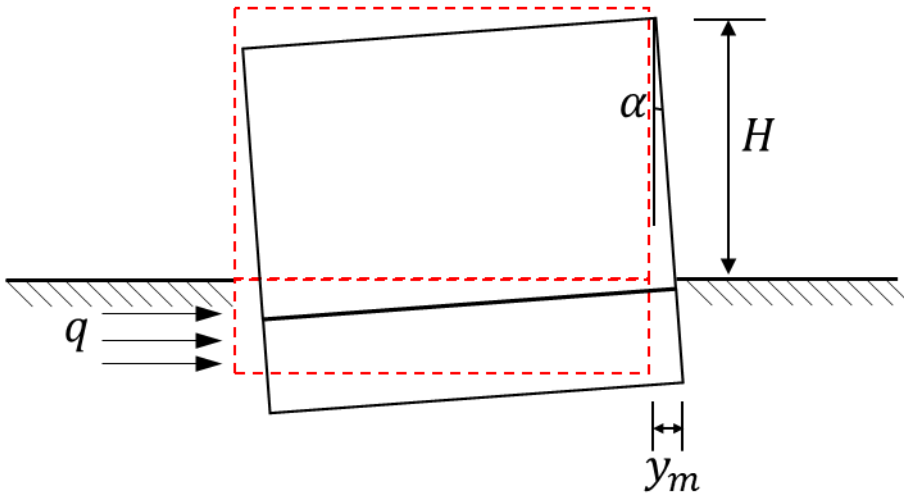


Fig 4. The inclination of the building

150 From *Technical Specification for Incline-rectifying of Buildings* (JGJ 270-2012), it is proposed that the incline angle of the building is the angle between the vertical plane of inclined building and the vertical plane of the original design building or the angle between the bottom plane of displacement foundation and the horizontal plane of foundation bottom of the original design. The angle α is the incline angle of the building shown in Fig 4. Furthermore, the inclination of the building is the tangent value of the incline angle.

155 Meanwhile, according to *Code of Deformation Measurement of Building and Structure* (JGJ 8-2007), we can calculate the inclination of the building which is the ratio of the horizontal difference between observation point on the top of the building and observation point on the bottom of the building to the vertical height of the building after tilted. The formula is as follows.

$$i = \tan\alpha = \frac{y_m}{H} \quad (9)$$

Where,

160 i --- the inclination of the building

α --- the incline angle of the building

y_m --- the horizontal difference between the top and bottom of the building

H --- the vertical height of tilted building calculated from the outdoor ground

It is worth pointing out that the building in our study case is regarded as a rigid building. So, the maximum horizontal

165 displacement of the foundation by using the simple beam mechanical model will be approximately the horizontal difference of the observation point at the top of the building relative to the observation point at the bottom.

The following is the equation for the inclination of the building:

$$i = \tan\alpha = \frac{y_m}{H} = \frac{1}{H} \left(\frac{5qL^4}{384EI} + \frac{3qL^2}{16GA} \right), \quad (10)$$

170 where i denotes the inclination of the building, which is the ratio of the maximum deformation y_m and the vertical height of tilted building calculated from the outdoor ground H .

2.2.2 Damage degree definition

In this study, the ratio of the building's inclination to the threshold value is represented as the damage degree. The damage degree is regarded as the output of physical vulnerability (Tarbotton et al.,2015, Kang et al.,2016). The degree of the building damage can be evaluated by utilizing some parameters, such as cracks in walls, inclination, the ratio of maintenance cost and the original value of building (Alexander, 1986; Chiochio et al., 1997; Cooper, 2008). Finno et al. (2005) reported that when highly stiff buildings are very inclined due to ground deformation, the wall cracking phenomenon is not obvious. On the contrary, if the stiffness of the building is lower, the cracking on the wall becomes serious. This research shows that using only cracks as an indicator is not suitable for vulnerability assessment. Other indicators, such as inclination, should also be taken into consideration. Therefore, the width of the cracks is not the only indicator for building damage assesment but we should also take into account if the building has inclined. Therefore, the inclination has been chosen to represent the deformation of buildings (Huang, 2015).

Moreover, the inclination of the building is easy to measure. The standard for dangerous building appraisal (JGJ125-

2016 China) provides the threshold value of the inclination of single- or multi-story buildings (Table 2). Buildings with inclination exceeding the threshold value are considered to be dangerous and uninhabitable.

185 **Table 2. The threshold value of building inclination (Ministry of Housing and Urban–Rural Development of PRC, 2016).**

Height (m)	$H_g \leq 24$	$24 < H_g \leq 60$	$60 < H_g \leq 100$
Threshold value i_m	1%	0.7%	0.5%

Here, H_g denotes the building height which is calculated from the outdoor ground.

By comparing the inclination of the building with the threshold value, the vulnerability (V) can be calculated as follows:

$$V = \begin{cases} \frac{i}{i_m} = \frac{1}{Hi_m} \left(\frac{5qL^4}{384EI} + \frac{3qL^2}{16GA} \right) & (i < i_m) \\ 1.0 & (i \geq i_m) \end{cases}. \quad (11)$$

The vulnerability (V) ranges from 0 to 1.0, value close to 1.0 indicates serious damage. Equation (11) demonstrates that

190 the building's inclination depends on the following three parameters: size, material, and foundation depth. To ascertain the

parameter with the highest significant impact on the degree of building damage, we can conduct a sensitivity analysis on these parameters by employing the principle of controlling variables.

2.3 Physical vulnerability function for masonry buildings

2.3.1 General functions

195 In this study, we obtained the physical vulnerability curve by relating building vulnerability with landslide safety factor (F_S). It is important to note that F_S is calculated for only the area where the building under study is located, but not for the whole landslide area. Landslide intensity is directly proportional to its stability situation. A higher intensity corresponds to a higher thrust force on the building foundation and lower landslide safety factor. Thus, we utilize the reciprocal value of F_S to be the landslide intensity in this study.

200 The relationship between building vulnerability and the landslide intensity was fitted by employing Weibull (1951) function that produces an S-shaped curve. This type of distribution curve has been proved to be the best for physical vulnerability analysis by Dario Peduto et (2017), Kang et (2016), Papathoma-Köhle et al. (2015), and Negulescu et (2010). Based on these findings, a modified Weibull function for calculating physical vulnerability is defined as follows:

$$V = 1 - e^{-a\left(\frac{1}{F_S}\right)^b}, \quad (12)$$

205 where V denotes physical vulnerability which is calculated by employing Eq. (11); F_S is calculated by employing Eq. (1); a and b are constants, which need to be determined.

2.3.2 Determination of constants by applying multiple scenarios

To determine the constants a and b in Eq. (12), we first obtain two or more scenarios, which can reflect the landslide safety factor and the building vulnerability. Using several triggering scenarios, such as rainfall, earthquake, and reservoir water level fluctuation, we can obtain several safety factors, the corresponding landslide force on building foundation, and the building vulnerability. Then, we apply the least-square method to obtain the constants based on the presupposed function in Eq. (12).

210 In this study, rainfall is the key triggering factor for the landslide. Thus, we obtain rainfall scenarios by analyzing the precipitation using different return periods. Pearson type (PT) III distribution model (Lei et al., 2018; Radwan et al., 2019) is applied because it is useful in rainfall-induced landslides; its probability density function is defined as follows:

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)} (x - a_0)^{\alpha-1} e^{-\beta(x-a_0)}, \quad (13)$$

215 where parameters α, β, a_0 , can be given by the following three statistical parameters after conversion: (\acute{x}, C_v, C_s). Thus, we have

$$\begin{aligned} \alpha &= \frac{4}{C_s^2} \\ \beta &= \frac{2}{\bar{x}C_vC_s} , \\ a_0 &= \bar{x} \left(1 - \frac{C_v}{C_s} \right) \end{aligned} \quad (14)$$

where \bar{x} denotes the average value, C_v denotes the coefficient of variation, and C_s denotes the coefficient of skewness.

220 From Eq. (14), the PT III distribution model has three undetermined parameters: \bar{x} , C_v , C_s . The principle of maximum entropy, the methods of moments, and maximum likelihood estimation are employed to estimate the parameters for the PT III distribution (Singh and Singh, 1988). We plot the physical vulnerability curve after obtaining the values of these three parameters determined by different rainfall scenarios with varying return periods.

3 Application of the proposed method

225 3.1 Geological settings and deformation of landslide

The Manjiapo landslide (110°10'0.32"E, 29°25'3.69"N), located in Sangzhi County, Zhangjiajie, China was selected as the case study (Fig. 5). The area is mountainous and hilly with elevation ranging from 154 m to 1890 m a.s.l. The climate is humid subtropical, and the estimated average annual rainfall is about 1400 mm.

230 The landslide covers an area of about $6.6 \times 10^4 \text{ m}^2$ with an average thickness of 6.9 m and an estimated volume of $45.5 \times 10^4 \text{ m}^3$. It demonstrates strip shape in a plan with a longitudinal dimension of about 560 m and the average width of approximately 176 m along the northwest (NW)–southeast (SE) direction. The elevation of the main crack is about 370 m a.s.l. The toe of the landslide is located at 272 m elevation along the stream.

235 The topography demonstrates a multi-step shape, the height of which ranges from 1 to 3 m. The middle and upper parts of the landslide are relatively gentle with a slope gradient of about 8°, while the lower part is steeper (12° slope). The sliding direction of the landslide includes two parts: the upper part orients at 335°, and the lower part at 313°.

240 The main materials of the landslide comprise loose debris from silty clay and siltstone, in which the latter only distributes in the middle and upper sections of the landslide (Fig. 6). The bedrock is argillaceous siltstone with a slope angle of approximately 10°. The shear-strength parameters of the slip soil of the landslide, shown in Table 3, are obtained from the detailed landslide report 2017 of the Hunan Institute of Xiangxi Geological Engineering Survey. The shear-strength parameters are based on 6 groups of undisturbed soil samples and their laboratory tests.

Table 3. Shear-strength parameters of Manjiapo landslide slip soils (data source: Hunan Institute of Xiangxi Geological Engineering Survey, China).

	Dry condition		Saturated condition	
	c/kpa	$\varphi/(\circ)$	c/kpa	$\varphi/(\circ)$
Average	11.98	9.09	5.85	6.84
Variance	1.56	2.25	0.79	0.64

Manjiapo landslide has a history of 10-year displacement. According to the residents, the landslide occurred in August

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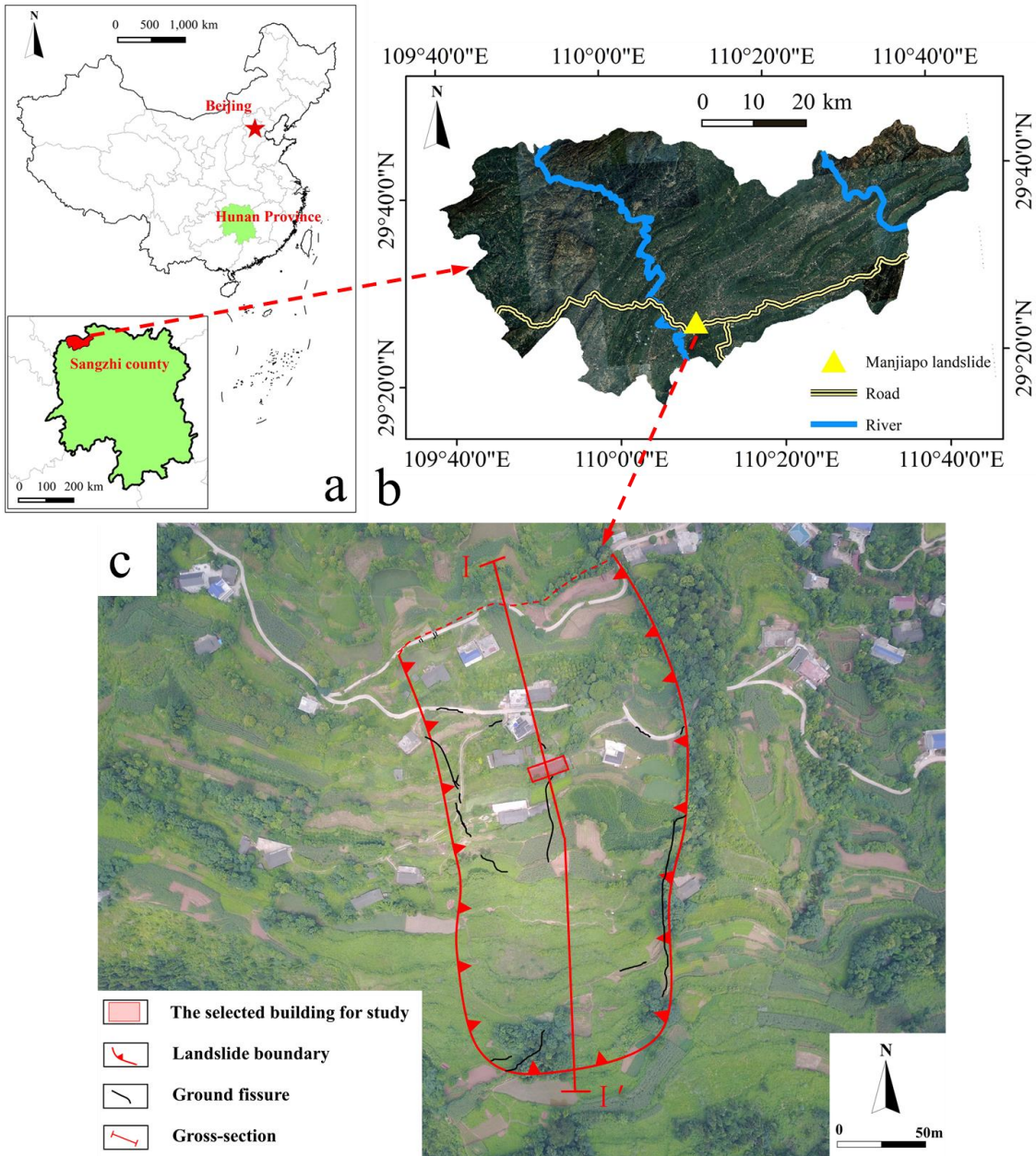
2008, which resulted in a few ground fissures. Due to heavy rain during 28th to 30th June in 2016 induced severe displacement of the landslide. Field investigation carried out in July 2017 revealed that the displacement mainly occurred in the middle and upper parts of the landslide (Figs.5c and 7a,b). Numerous tension cracks in the upper part had a visible depth of 2–5 cm, with a length of 1 600 to 6 600 cm and a width of about 15 cm . In the middle part of the landslide, staggered extrusion deformation can be observed locally apart from numerous tension cracks.

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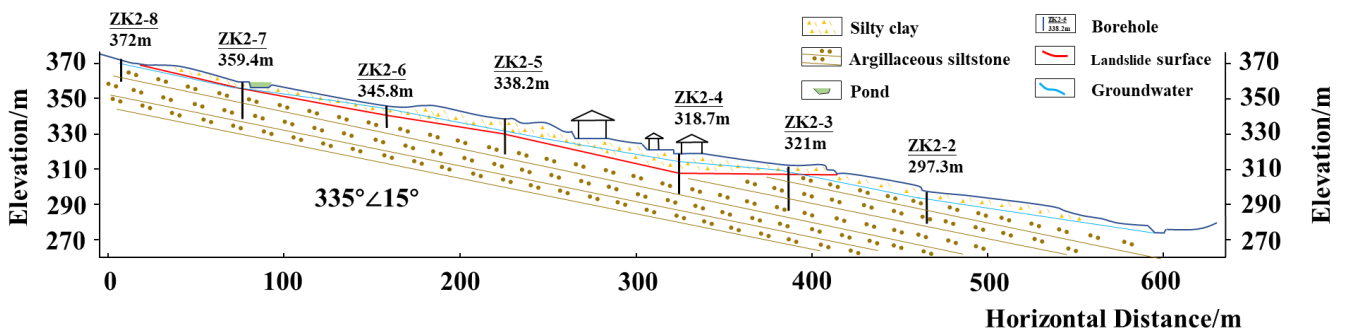
Moreover, the surface deformation caused the rise of groundwater in the silty clay layer. As a result, the shear strength of the soil mass decreased and the sliding zone was formed. It was revealed by boreholes dug during fieldwork in 2017. On the lower part of the landslide, cracks and some uplift deformation were observed on the roads (Fig. 7c).

255

Rainfall appeared to be the most important triggering factor of the slow-moving Manjiapo landslide. The cracks and the macroscopic deformation on the landslide were monitored since 2016. Analysis of the monitoring data shows that only heavy rainfall could reactivate the landslide. Analysis of the borehole data shows that the groundwater table is stable in the dry season. The landslide did not show any displacement in the absence of extreme rainfall. For example, the cracks on the landslide did not expand, and there were only a few new cracks.



260 Fig. 5. Location of the Manjiapo landslide, a) map of China download from <http://www.geodata.cn>, b) a Google Earth image fragment showing the location of the landslide, and c) an Unmanned Air Vehicle (UAV) image showing the landslide boundary and the location of a cross-section I-I' (UAV image obtained during field investigation).



265 Fig. 6. Geological profile (1:1 000) of section I-I' of the Manjiapo landslide. The location of the cross-section is shown in Fig. 5c.

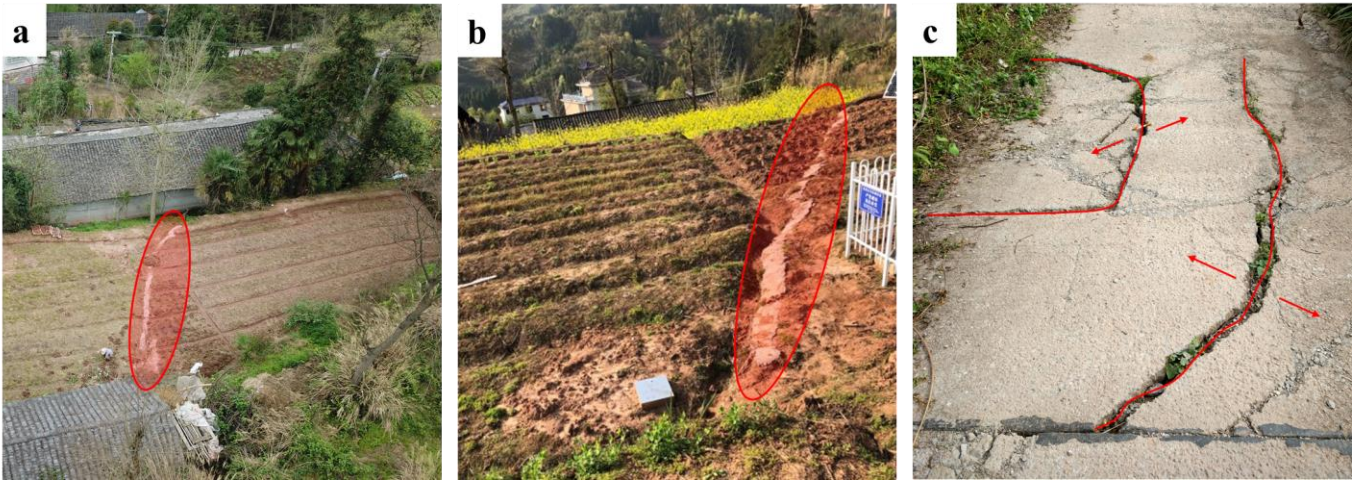


Fig. 7. Cracks on the Manjiapo landslide: (a) the middle part, (b) the upper part, and (c) the lower part.

3.2 Damaged buildings on the landslide

Field investigation, carried out in July 2017, shows that 15 houses were affected by the landslide, of which 5 were constructed using brick-wood and 10 brick-concrete (Fig. 8). The buildings located in the middle part of the landslide were the most severely damaged. Due to landslide deformation, the walls of these buildings were cracked and inclined. We selected a damaged building for a detail study. Severe cracks appeared on the walls, and finally, the building was abandoned.

The selected building for study is a story masonry building with a length of 25 m and a width of 9 m. The building has six rooms, and each room was damaged as a result of continuous rain from June 28th to 30th in 2016. Large-scale ground collapse occurred in rooms C, D, and E (Fig. 9). Meanwhile, the walls of these rooms developed numerous diagonal cracks with width varying from 2 to 8 cm. The walls were heavily tilted, with inclination varying from 0.7% to 1.0% (Fig. 10a,b,c).

Table 4. Parameters of the building on Manjiapo landslide

For building				For foundation			Soil depth where the building located (m)
Length L (m)	Width W (m)	Height H (m)	Depth d (m)	Young's modulus E (MPa)	Shear modulus G (MPa)	E/G	
25	9	2.8	1	2250	865	2.6	5

Remark: The elastic modulus value is called the code for the design of masonry building (GB50003-2011). Thus, an isotropic elastic material is defined as follows: $E/G = 2(1 + \nu)$, where ν denotes the Poisson's ratio for $\nu = 0.3$, and $E/G = 2.6$ (Burland, 1977). H denotes the vertical height of tilted building calculated from the outdoor ground.



Fig. 8. A typical example of a damaged building in the landslide area (Unmanned Air Vehicle image obtained during field investigation).

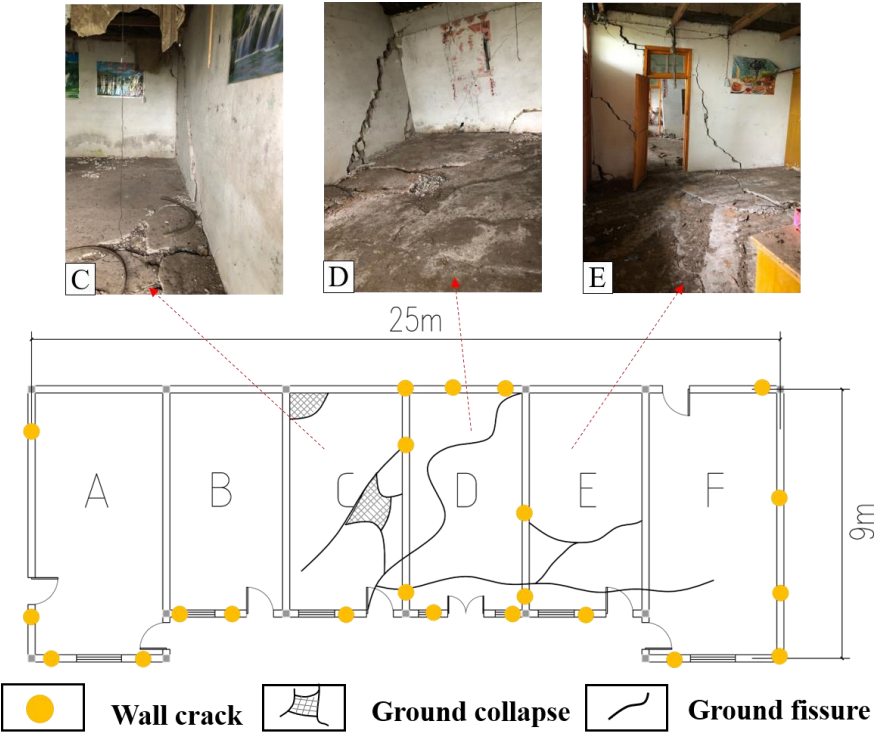


Fig. 9. Floor plan of the case study building.

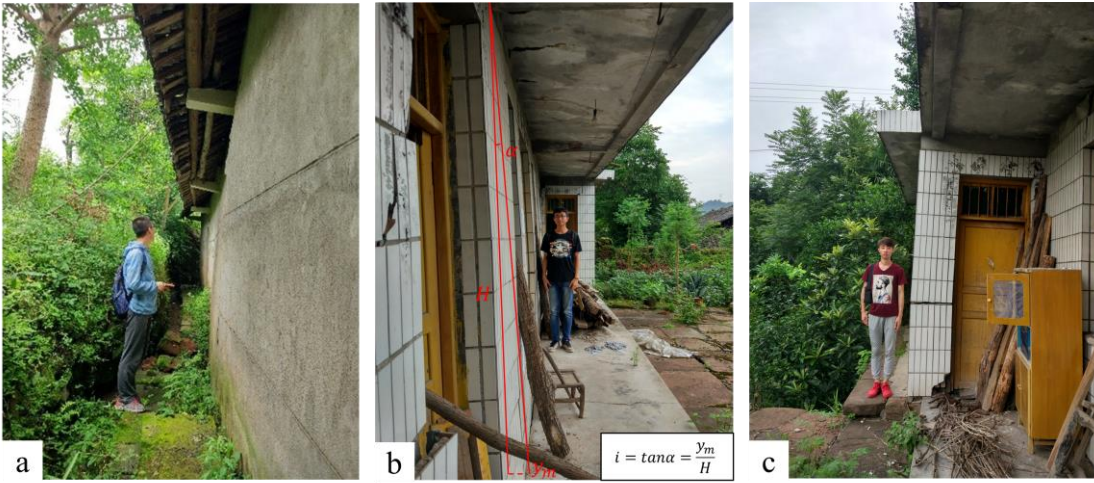


Fig. 10. The integral decline state of the case study building:(a) the back wall of the building with inclination of 1.0%,(b) the front wall of the building with inclination of 0.8%,(c) the front wall of room A (shown in fig 9)with inclination of 0.7%

290 **3.3 Rainfall data analysis**

Landslides are induced by extreme or short-term sustained intense precipitation (Chen et al., 2014; Qiong et al., 2018; Huang et al., 2014). Furthermore, 3-day rainfall proved to be the most relevant parameter of landslide occurrences in the study area (Lin et al., 2018). Precipitation data of Sangzhi County for the period 1995 to 2016 were collected from the site <http://www.cma.gov.cn/>. The data was analyzed for extreme rainfall and scenario determination (Fig. 11).

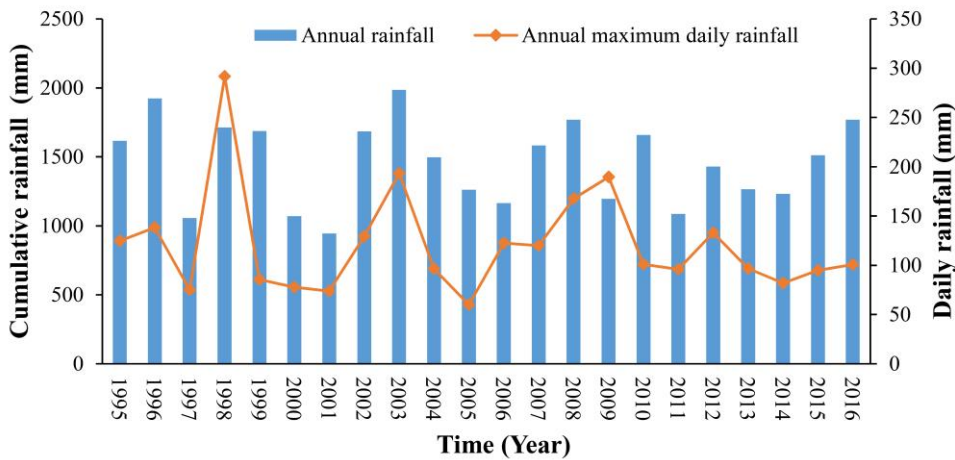


Fig. 11. Annual and maximum daily rainfall in the study area during the period of 1995–2016.

4 Results

4.1 Extreme rainfall scenarios and landslide residual thrust calculation

The extreme rainfall distribution curve is depicted in Fig. 12 that is constructed by employing PT III distribution model and the rainfall data collected for the period 1995-2016. Using this curve, we can obtain the amount of 3-day cumulative precipitation corresponding to each return period.

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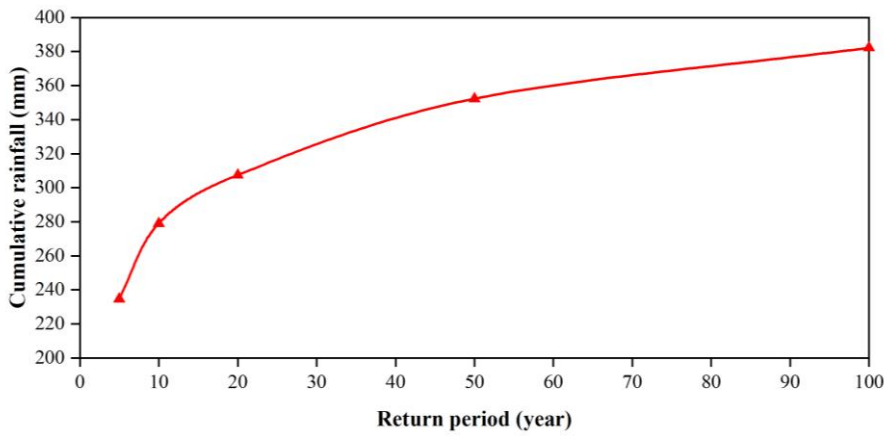


Fig. 12. The extreme rainfall distribution curve.

Groundwater levels based on four scenarios with different magnitudes of rainfall were selected: (a) dry condition, no rain; (b) rainfall with a return period of 5 years (3-day precipitation 235 mm from Fig. 11); (c) rainfall with a return period of 10 years (3-day precipitation 279 mm from Fig. 11); (d) rainfall with a return period of 50 years (3-day precipitation 352 mm from Fig. 11). For scenarios b, c, and d, rainfall data was utilized as the boundary condition to simulate the groundwater level of the landslide. Note that all the scenarios are assumed without the influence of an earthquake.

The SEEP/W code (GEOSTUDIO) was applied to analyze the groundwater seepage of Manjiapo landslide to obtain the amount of 3-day cumulative precipitation corresponding to each return period by using PT (Pearson type) III distribution model (Fig. 12). The average amount of 3-day cumulative precipitation is input to the software in turn, and the groundwater under the rainfall scenarios is simulated.

The saturated volumetric water content is 0.4 by cutting the ring method. The saturated permeability coefficient is obtained by back analysis. We choose the saturated volumetric water content and the permeability coefficient by the variable-controlling approach. Three groups of input values are: 0.4, 0.1; 0.4, 0.2; 0.4, 0.3. Then, the groundwater is simulated and validated for the rainfall event in March 2018. The root mean square error (RMSE) is utilized to check the accuracy. Lower RMSE means smaller error and better prediction. The results of the RMSE are shown in the following table. The saturated volumetric water content is 0.4 and the most suitable permeability coefficient is 0.3 m/d.

Table 5. Permeability coefficient back analysis of the rainfall event in March 2018, by comparing the root mean square errors (RMSE) of three hydrological gauges (installed by the authors in December 2017, see Fig.5) on the Manjiapo landslide

The permeability coefficient (m/d)	0.1	0.2	0.3
RMSE (STK-1)	2.280	2.222	2.154
RMSE (STK-2)	0.860	0.677	0.615
RMSE (STK-3)	2.540	2.491	2.405

Note: the saturated volumetric water content by Lab test is 0.4.

The results of the residual thrust and the corresponding safety factor are presented in Table 6. These values were obtained by the landslide residual force calculation method (section 2.1) for the geological profile (Fig. 6). In the dry season (scenario

a), the landslide performs residual thrust of 142 kN/m and safety factor for the area where the case study building is located of 0.853, while these values can change significantly in rainy season (scenario b, c and d). For an example, the residual thrust can be increased by at least 15 times and the safety factor can be reduced by nearly half in the rainy season with a 50-year rainfall. This indicates an important influence of rainfall on landslide stability and the building's safety.

Table 6. Landslide residual thrust, pushing force on the building's foundation, and vulnerability of the building based on four scenarios ((a) dry condition ; (b) rainfall with a return period of 5 years (3-day precipitation 235 mm/d) ; (c) rainfall with a return period of 10 years (3-day precipitation 279 mm/d) ; (d) rainfall with a return period of 50 years (3-day precipitation 352 mm/d)).

Scenarios	F_{sb}	F_s	F(kN/m)	q (kN/m)	i (%)	V
a	0.853	1.457	142	28	0.053	0.053
b	0.529	0.819	1756	351	0.656	0.656
c	0.481	0.778	2040	408	0.762	0.762
d	0.428	0.632	2638	528	0.985	0.985

Here, F_{sb} denotes the factor of safety for the area where the building is located.

4.2 Results of scenario-based vulnerability curve of the building

As described earlier in section 3.1 and demonstrated in the geological profile (Fig. 6), the sliding mass material is silty clay and bedrocks. Therefore, the thrust distribution form can be considered as rectangular based on Table 1. By applying the results of the horizontal component of landslide residual thrust (using the method in section 2.1) and the soil depth where the building is located (Table 3), the pushing force on the foundation was calculated by the corresponding thrust distribution function.

Table 6 illustrates the results of pushing force on the foundation, inclination, and the building vulnerability based on different scenarios. The result indicates that the building's vulnerability is very low ($V = 0.053$) in the dry season, with a pushing force of 28 kN/m on the building's foundation. However, in rainy seasons, the building can experience severe damage with the vulnerability of 0.798 (10-year rainfall) or even 0.985 (50-year rainfall).

Using the four sets of scenario data (Table 6), we constructed the physical vulnerability function and the constants in Eq. 12 were determined by employing the Weibull function.

Based on the Chinese standard of *Specification of Risk Assessment for Geological Hazard* (DZ/T 0286-2015), there are three stability states of landslide according to the range the safety factor (F_s) of landslide. Please see more details in the following table 7.

Table 7. The range of safety factor (F_s) of landslide and its state (referred to Ministry of Land and Resources of the PRC, 2015)

The safety factor F_s	$F_s \leq 1.00$	$1.00 < F_s \leq F_{st}$	$F_s > F_{st}$
Stability state of landslide	unstable	Less stable	stable
Description	(1) Many newly expanded cracks on the ground and new deformation on buildings and vegetation. (2) Obvious scratch	(1) Local deformation on the ground. (2) No obvious deformation on the main scarp. (3) No obvious expansion of	(1) No sustained deformation on the ground. (2) No crack expansion on the landslide. And no new deformation on buildings

and displacement on the main scarp. (3) Cracks on the crown of landslide.	the cracks on the buildings. (4) Small cracks on the crown of landslide.	and vegetation on the landslide. (3) No scratch and obvious displacement on the main scarp.
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Note: F_{st} denotes the design safety factor.

The value of F_{st} is defined based on the slope safety level and slope type. Meanwhile the slope safety level is defined based on the potential economic loss and element at risk. According to the field investigation, there are 116 residents in the affected area of the Manjiapo landslide, and the road passes through the middle part of the landslide. In case of geologic hazard, it will threaten the lives and property of 116 residents and damage more than 67,000 square meters of the land. At the same time, the road will be damaged, threatening the safety of the pedestrians and passing vehicles. The potential economic loss will be more than CNY 5 million. Based on the table 9, the safety level of the Manjiapo landslide is judged to be second level.

Table 8. The value of the design safety factor (referred to Ministry of Housing and Urban–Rural Development of PRC, 2013)

the slope safety level		First level	Second level	Third Level
Permanent slope	General condition	1.35	1.30	1.25
	Earthquake condition	1.15	1.10	1.05
Temporary slope		1.25	1.20	1.15

Table 9. The slope safety level (referred to General Administration of Quality Supervision, Inspection and Quarantine of the PRC, 2016)

the slope safety level		First level	Second level	Third Level
potential economic loss (CNY)		≥ 50 million	5 million to 50 million	< 5 million
Element at risk	population	≥ 500	100 to 500	< 100
	Infrastructure	Very important	Important	less important

Note: If one of the conditions is met, it will be judged to be the corresponding slope safety level.

So, when the safety factory of the Manjiapo Landslide is greater than 1.30, the landslide is stable and the landslide intensity is very low. In addition, the resistance ability of the building can prevent the building from being destroyed by the low intensity of the landslide (Du, 2013). In summary, the physical vulnerability of the building on Manjiapo landslide is very low when the safety factory is greater than 1.30. It provides that the physical vulnerability of the building on Manjiapo landslide is 0 when the reciprocal value of the safety factor is 0.5. The physical vulnerability of the case study building on Manjiapo landslide is demonstrated in Fig. 13.

We can observe that the physical vulnerability is very low when the landslide is stable with a safety factor greater than 1.0. When the safety factor is lower than 1.0, the physical vulnerability rapidly increases. Vulnerability approximates 1.0 when the reciprocal value of the safety factor is 2.5. By utilizing this curve, we can obtain the possible physical vulnerability of the building if the safety factor of the landslide is known. Therefore, we need to demonstrate that the safety factor is for the local area where the case study building is located, but not for the whole landslide.

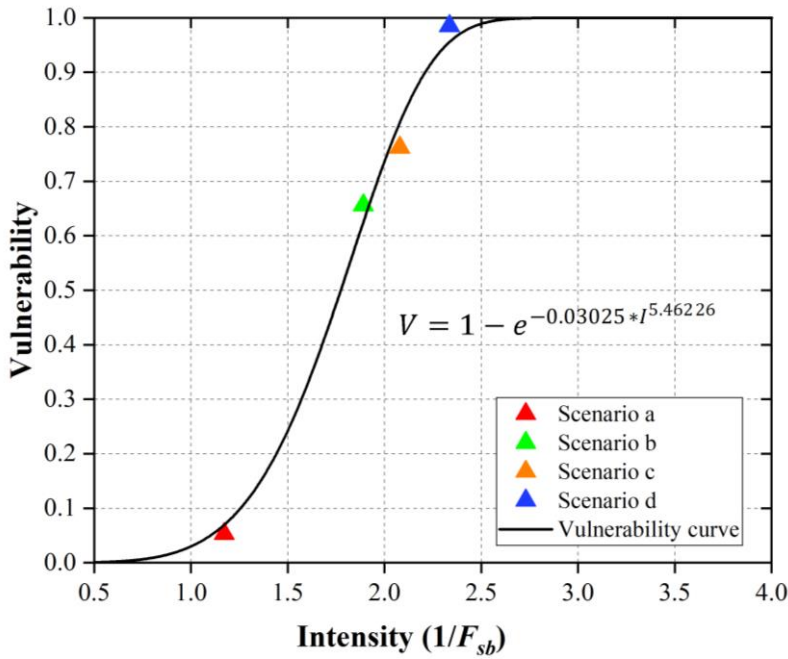
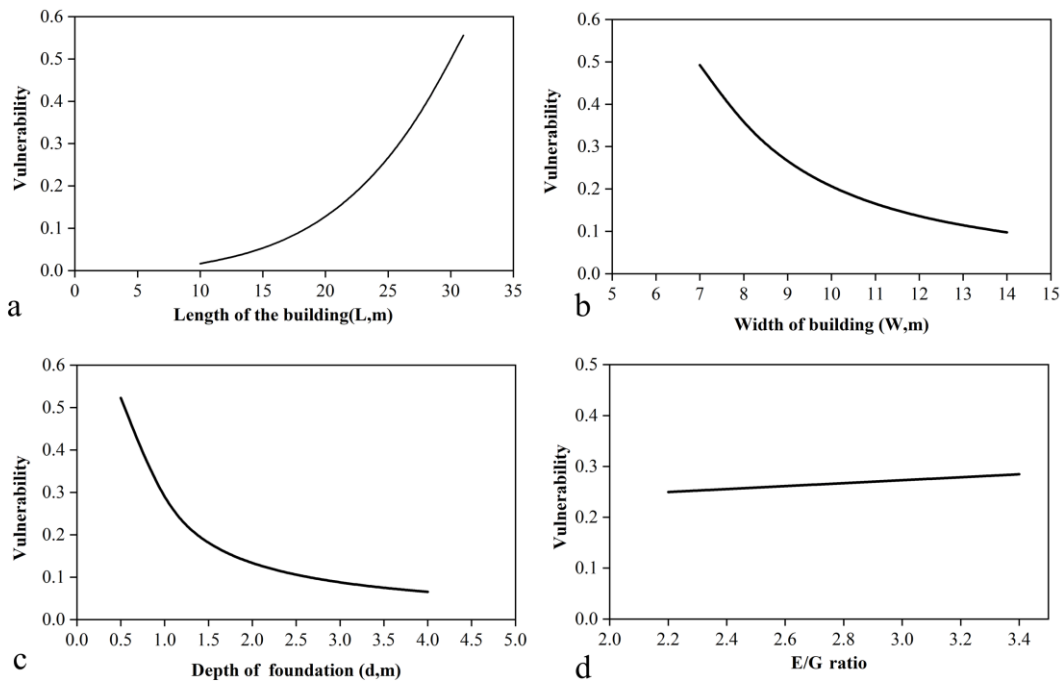


Fig. 13. The physical vulnerability curve for masonry buildings impacted by the slow-moving landslides.

4.3 Influence of building characteristics on vulnerability and the sensitivity analysis

375 To obtain the influence of building characteristics on vulnerability, we conducted sensitivity analysis. We know that numerous parameters of the building were included in the building inclination and vulnerability calculation e.g. length, width, depth of foundation, and E/G ratio . We conducted sensitivity analysis by changing the values of each parameter in step while keeping others constant and estimated the possible physical vulnerabilities of the building. The results are shown in Fig. 14.



380 Fig. 14. Vulnerability curves for different building parameters: a) length, b) width, c) depth of foundation, and d) E/G ratio.

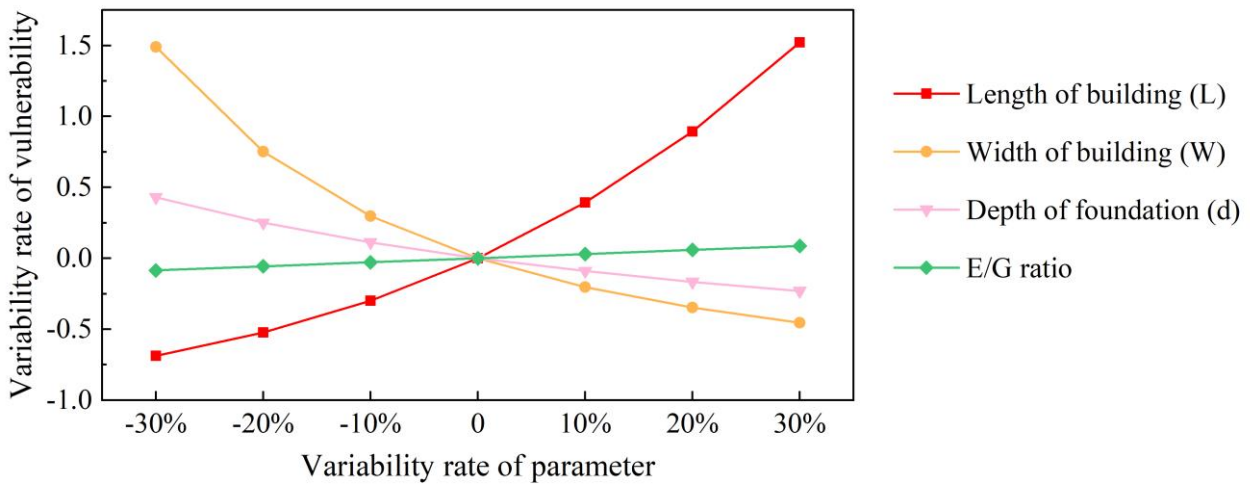


Fig. 15. The sensitivity analysis of building parameters for physical vulnerability.

As demonstrated in Fig. 14, we observe that the physical vulnerability is directly proportional to the building length, E/G ratio and is inversely proportional to the other parameters: building width, and foundation depth. It also shows that the higher the ratio of building length and width, the more vulnerable to damage the building is. Besides, buildings with deeper foundation and higher E/G ratio have higher resistance.

The results of the sensitivity analysis of the building parameters are demonstrated in Fig. 15. The red line that represents length has the steepest slope among all the lines, indicating that the length of the building has the most significant influence on the physical vulnerability of building. We can simultaneously obtain the second major factor that is the width of the building, while the third one is the foundation depth.

We tested four types of buildings with different lengths: 15 m, 20 m, 25 m, and 30 m (Fig. 16(a)). When F_{sb} is greater than 1.0, the building physical vulnerability with any length is very low, that is, almost no damage. In addition, the building demonstrated a different performance when F_{sb} is less than 1.0. The building physical vulnerability with length 15 m was slightly increased when the landslide stability was getting worse. However, the building physical vulnerability with length 30 m rapidly increased when F_{sb} was less than 1.0. This indicates that the buildings on the location where the target building stands have a limit length of 30 m. When the length of the building was greater than 30 m, the building faced severe damage if F_{sb} was less than 1.0.

To further test the detailed influences of the building parameters, we select the top two parameters based on the above results of sensitivity analysis: building length and width. Two sets of physical vulnerability curves are depicted in Fig. 16, and the corresponding functions of building physical vulnerability at the three scenarios are presented in Table 10.

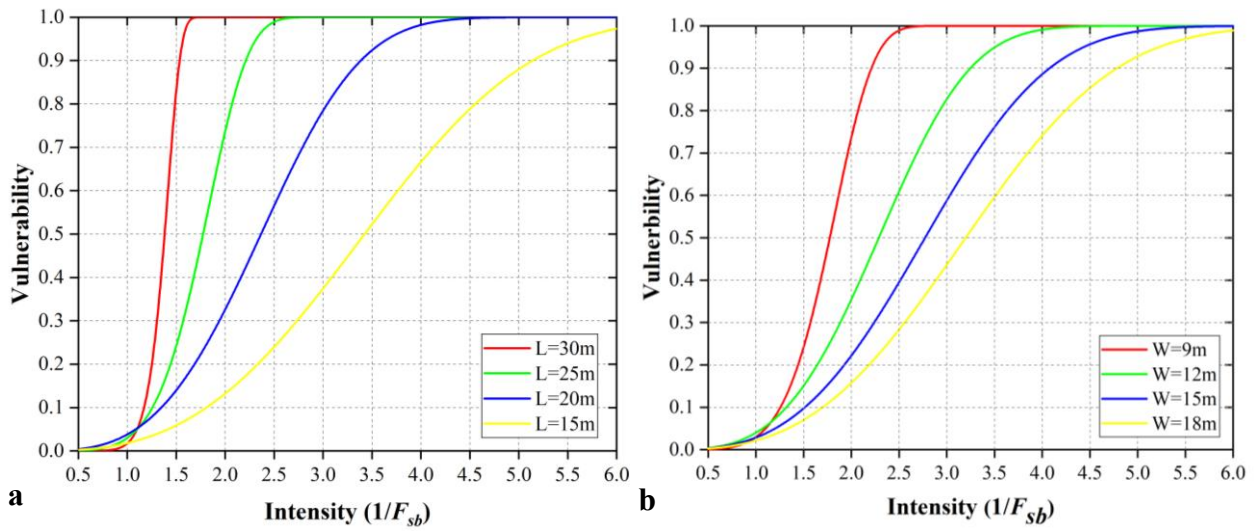


Fig. 16. Physical vulnerability curves of buildings with different parameters: (a) length and (b) width.

Physical vulnerability curves of buildings with various building width are depicted in Fig. 16(b), while the physical vulnerability curves of buildings with various lengths are depicted in Fig. 16(a). The difference in the physical vulnerability of the buildings with different building width is not significant when the F_{sb} is greater than 1.0. Meanwhile, the building with building width 9.0 is susceptible to the changes of F_{sb} . A rapid increase of building damage with such building width occurs when the F_{sb} is less than 1.0. When the building width is close to the building length, the vulnerability of the building is low under the same value of F_{sb} .

Table 10. Physical vulnerability functions of buildings with different lengths and width based on various scenarios.

Parameters	Scenarios	F_{sb}	F (kN/m)	i (%)	V	vulnerability function	
Length (L/m)	15	a	0.853	142	0.010	0.010	$V = 1 - e^{-0.01827*(1/F_s)^{2.9535}}$
		b	0.529	1756	0.128	0.128	
		c	0.481	2040	0.149	0.149	
		d	0.428	2638	0.193	0.193	
	20	a	0.853	142	0.025	0.025	$V = 1 - e^{-0.03869*(1/F_s)^{3.34957}}$
		b	0.529	1756	0.312	0.312	
		c	0.481	2040	0.362	0.362	
		d	0.428	2638	0.469	0.469	
	25	a	0.853	142	0.053	0.053	$V = 1 - e^{-0.03025*(1/F_s)^{5.46226}}$
		b	0.529	1756	0.656	0.656	
		c	0.481	2040	0.762	0.762	
		d	0.428	2638	0.985	0.985	
30	a	0.853	142	0.101	0.101	$V = 1 - e^{-0.01735*I(1/F_s)^{11.41247}}$	
	b	0.529	1756	1.239	1.000		
	c	0.481	2040	1.440	1.000		
	d	0.428	2638	1.862	1.000		
Width (W/m)	9	a	0.853	142	0.053	0.053	$V = 1 - e^{-0.03025*(1/F_s)^{5.46226}}$
		b	0.529	1756	0.656	0.656	
		c	0.481	2040	0.762	0.762	
		d	0.428	2638	0.985	0.985	
	12	a	0.853	142	0.027	0.027	$V = 1 - e^{-0.04074*(1/F_s)^{3.42469}}$
		b	0.529	1756	0.338	0.338	
		c	0.481	2040	0.393	0.393	
		d	0.428	2638	0.508	0.508	
	15	a	0.853	142	0.017	0.017	$V = 1 - e^{-0.029*(1/F_s)^{3.11232}}$
		b	0.529	1756	0.214	0.214	

	c	0.481	2040	0.249	0.249	
	d	0.428	2638	0.322	0.322	
	a	0.853	142	0.012	0.012	
	b	0.529	1756	0.153	0.153	
18	c	0.481	2040	0.177	0.177	$V = 1 - e^{-0.02169*(1/Fs)^{2.97989}}$
	d	0.428	2638	0.229	0.229	

410 5 Discussion

We developed a scenario-based mechanical method for analyzing the physical vulnerability of buildings on slow-moving landslides. The method enabled us to analyze the physical vulnerability from a mechanical view on soil-structure interaction, which can help us to better understand the building damage on the slow-moving landslides and is useful for physical vulnerability assessment of masonry buildings located on slow-moving landslides. By inputting the geometry parameter (length and width of the building) and the safety factor of the area where buildings located, the potential vulnerability can be obtained by using the vulnerability functions we provided in this study.

The results of the application correspond to the fact from the field investigation. As described in section 3.2, the building damage occurred due to rainfall from June 28th to 30th, 2016. the calculated physical vulnerability is observed to be 0.762 (Table 5), which is close to the real damage measured in the field varied from 0.7 to 1.0 (Fig. 10a,b, and c). Herein, the influence of building parameters (length, width, height, foundation depth, etc.) on physical vulnerability corresponds to other previously conducted studies (Li et al., 2010; Du et al., 2013; Corominas et al., 2014). This is consistent with the study conducted by Corominas et al. (2014) that the typology of buildings is a key factor in the quantification of physical vulnerability.

The vulnerability functions from this study is suitable for the masonry buildings which are located on slow-moving landslides and are perpendicular to the slope direction. The case study building is oriented along the contour lines or nearly perpendicular to the direction of the slope or the landslide. If the building was oriented parallel to slope direction, the damage would not have been so severe. It is revealed by the results obtained from the sensitivity analysis of building parameters in the assessment of vulnerability. In the case of buildings perpendicular to slope direction, the larger the building length, the more serious is the building's damage with the same force of landslide. The case study building (25 m long) showed much damage, it almost collapsed when the landslide occurred. Our study shows that the building length perpendicular to the sliding direction of the landslide should not be too large. We note that 30 m is the threshold value for the length of masonry buildings. Physical vulnerability will be decreased if the building width is increased and the length is decreased considerably (Fig 14 a and b). In this case the orientation of the building will be changed in such a way that the longest axis of the building is in the same direction of the slope. Therefore, we suggest that it is important to consider the building length-width ratio as well as the orientation of the buildings in land-use planning for the development of settlements on sloping areas.

435 Since the output of physical vulnerability is related to the safety factor for the area where the building is located, it is possible to evaluate the physical vulnerability of buildings prone to slow-moving landslides at a regional scale. For instance, the distribution of F_S can now be obtained from several studies (Muntohar et al 2009, Takara K et al 2010, Salciarini et al 2006 and Sorbino et al 2010). If we employ the physical vulnerability curves or the curves from this study, the risk can be quantified for the potential losses of buildings based on the F_S analysis for landslides at regional scale. But the application of physical
440 vulnerability assessment at the regional scale should be tested first before implementing regional land use planning activities.

The research is based on detailed field investigation, monitoring, and analysis in such specific landslides and case building. Concerning the limitation of this study, it is important to mention that the results are applicable for the similar geological background areas prone to slow-moving landslides or similar landslide displacement process. The quantitative relationship between the physical vulnerability of buildings and landslide displacement process is very weakly studied around the world.
445 It needs more concentration of studies. Moreover, the physical vulnerability assessment was carried out for the building which is located inside the landslide area for which soil pressure on the foundation is suitable. Our study does not include the estimation of vulnerability for the buildings which are located acrossing the boundary of the landslide, the result of which may be a bit different. Also, we did not consider the friction between the foundation and soil, and also uncertainty analysis was not performed. In future studies, more relative mechanical models are required. Similarly, random distribution of soil parameters
450 for landslide F_S calculation, such as shear strength, can be considered for generating fragility curves based on this study. Currently, intensive researches on slow-moving landslides vulnerability in the Three-gorges Reservoir (Zizheng G et al 2020) is strengthened, where the authors are applying our approach for more case studies. This approach will be verified and modified through continuing studies.

6 Conclusions

455 We propose a method for constructing physical vulnerability curves and functions by utilizing the analysis of the horizontal force of landslide acting on the foundation and the physical response of the building. The proposed method was applied to slow-moving landslides in China, for which a severely damaged building was considered as the case study structure.

The proposed method mainly comprises calculating the landslide safety factor and horizontal load on foundations based on different scenarios (extreme rainfall with different return periods); the physical response of foundation and the inclination
460 of the building was also analyzed. Finally, the physical vulnerability curves were generated by applying the Weibull function.

Good consistency between the estimated physical vulnerability and on-field damage evidence was observed in the case study building. The sensitivity analysis of the building characteristics revealed that building length and foundation depth are the main determining factors in the physical vulnerability in the slow-moving landslides. The larger the building length, the

higher is the vulnerability. Apart from the length, the orientation of the building seems to be equally important. Thus the
465 building length, especially if it is oriented perpendicular to the sliding direction of the landslide, should not be too large. We
hope that this study can be a useful supplement for the physical vulnerability estimation of buildings in the area prone to slow-
moving landslides.

Data availability. The study relied on two sets of data: (i) the data collected by the fieldwork, (ii) the detailed landslide
investigation reports provided by the China Geological Survey (Hunan Institute of Xiangxi Geological Engineering Survey).
470 The data is included in Section 3 in this paper.

Author contribution. Qin Chen and Lixia Chen discussed the research plan, carried out the fieldwork, carried out the modelling
part, and wrote the paper. Qin Chen prepared the figures for the paper. Lixia Chen and Kunlong Yin supervised the research.
Lei Gui and Xuelian Cao helped in modelling. Lei Gui and Juan Du helped in data collection. Shrestha helped in research
paper development and English writing.

475 **Competing interests.** The authors declare that they have no conflict of interest.

Special issue statement. This article is not a part of any special issues. It is not associated with a conference.

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480 dynamic response of the quantitative vulnerability of buildings in different evolution stage of landslides” financed by the
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