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Review of the numerical simulation study on glacial/rock fall-avalanches

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Abstract: *With the increasing frequency of extreme events around the world, ice avalanche debris flow has become one of the major hazards threatening high altitude areas. In this paper, the study of this kind of disasters is carried out, the technical means of disaster research and the mechanism of disaster are analyzed, and the numerical simulation inversion of typical disasters is carried out. The conclusions are as follows: (1) At present, multi-source remote sensing images, DEM, seismic records and meteorological data are mainly used for analysis, which reveals that precipitation, temperature and seismic activity are the main factors of disaster; (2) Numerical simulation and large-scale laboratory experiments, as the main means, are used to analyze the mechanism of debris flow, revealing the physical and mechanical mechanism of ice-rock mixture in the disaster-causing process; (3) It is a developing trend to use discrete element numerical simulation to study the movement process of ice avalanche debris flow and the process of disaster chain caused by it; (4) The use of PFC numerical simulation software to study the typical ice-rock collapse debris flow disasters in Sedongpugou is of applicable value.*

Keywords: *Ice rock debris flow, disaster mechanism, disaster chain, discrete element numerical simulation*

1. Introduction

After entering the 21st century, the global climate has undergone significant changes, and extreme climate events have generally increased [1]-[4]. As the third pole of the earth and the water tower of Asia, the Qinghai–Xizang Plateau has the largest modern glacier in the middle and low latitudes of the world , and the warming rate in recent decades is twice that of the global average in the same period, reaching 0.3-0.4 °C/10a[5]-[8]. The Qinghai-Xizang Plateau has complex topography, developed faults and active internal dynamics, and a large amount of loose solid materials are generated under the earthquake and ice erosion, which provides favorable conditions for the occurrence of various mountain disasters [9]-[11]. The ice collapse disaster in the Qinghai-Xizang Plateau has become one of the major geological disasters. The risk is mainly manifested as the debris flow formed by the ice avalanche in the sliding process, which threatens the life and property safety of downstream people [12]-[18].

Understanding the movement mechanism of high altitude and high drop of high speed remote ice avalanche debris flow is of great significance for disaster identification and prevention. In this paper, the induced factors, movement mechanism and research status of ice avalanche debris flow are systematically described, and the research progress of effective inversion of debris flow and other disasters by means of discrete element numerical simulation is analyzed, and then the disaster inversion of typical cases is carried out by means of discrete element numerical simulation, in order to provide some technical reference for the subsequent research.

2. Ice avalanche debris flow

Ice avalanche debris flow is a special high-speed remote landslide that carries ice debris during initiation or movement [19]-[24]. Its provenance is widely distributed in almost all the alpine mountains on Earth, including the Himalaya-Karakoram Range, the Alps, the Caucasus Mountains, the Alaska Range, the Pacific Coast Range (including the Rocky Mountains and the Andes Mountains), and the Southern Alps [19]. It has gradually become a hot and frontier issue in the research field of geological hazards in the context of global warming [19].

2.1 Disaster mechanism

In view of the problem of ice collapse, Tong Liqiang et al. studied the distribution and change of glaciers in the Sedongpu Basin in southeast Xizang in the past 40 years on the basis of medium-high resolution multi-source remote sensing images such as Landsat [12]. Tang Minggao et al. analyzed the evolution process and influencing factors of ice collapse disaster based on multi-period image data of Sedongpu, and carried out shear experiments on ice media at different temperatures to reveal the causation mechanism of ice collapse in Sedongpu. [25] Zhang Longyu et al. used SAR Offset-Tracking technology to obtain glacier deformation as a supplement to SBAS-InSAR, calculated pre-disaster deformation of the basin from January to October 2018, and jointly analyzed the overall pre-disaster deformation of the basin and its influencing factors. [26] Tong Liqiang et al. sorted out eight events of debris flow blocking Yarlung Zangbo River in the Sedongpugou basin since 2014, and explored the reasons for frequent debris flow events in the basin by combining radar data and meteorological data.[12] Gao et al. used UAV and InSAR technology to interpret the present geomorphology of Sedongpu and the volume and geomorphologic changes of moraines since 2017 in detail. [27] Through comprehensive analysis of the time series and trigger factors of deformation and snowmelt changes before the disaster, Zhu Bangyan et al. Retrieved glacier deformation in Sedongpu basin from April 2018 to October 2018 by SBAS-InSAR technology using 30 sentinel-1 SAR images, revealed that the combined effects of snowmelt, rainfall, earthquake and climate change caused ice avalanche and debris flow.[28] Ding et al. also came to a similar conclusion, believing that precipitation, temperature and seismic activity were the main triggers controlling the dynamic mechanism of glaciers and the final collapse event. [29]

2.2 Movement mechanism

Ice avalanche debris flow is often characterized by large scale, fast speed, long sliding distance and polymorphism [17]. The high-speed characteristics of ice rock debris flow are not only related to gravity, but also related to the drag reduction mechanism during the movement. Ice is not only one of the main components of ice rock clastic flow, but also a low-friction material, which can be used as a material component to reduce drag, but also as a topographic surface drag reduction [21]. In order to clarify the superfluidity mechanism of large-scale landslides, He et al. extended the thermal-hydrodynamic (THM) coupling analysis to the study of ice-rock avalanches considering the ice-water phase transition caused by frictional heating in order to clarify the superliquidity mechanism of large landslides. [30] Schneider et al. simulated the fluidizing process caused by frictional heat melting of ice-rock debris flow through a rotating drum experiment, and realized the fluidizing state transformation of ice-rock debris flow from solid to fluid state for the first time in the laboratory, and found that the volume friction coefficient of ice-rock mixed materials showed a linear decreasing trend with the increase of ice content. [31] Dong et al. also found through the drum experiment that changes in ice content and meltwater volume directly affect flow composition, resulting in significant changes in flow behavior and basement stress. Stress fluctuation increases with the increase of static load, and is positively correlated with particle size and velocity, and negatively correlated with meltwater volume in constant volume and constant weight flow. [32] In addition, Huai et al. analyzed the characteristics and mechanism of glacier disasters using multi-source data such as remote sensing images, DEM (digital elevation), seismic records and meteorological data.[33] Ding et al. carried out offset tracking processing on 7 Sentinel-1A synthetic aperture radar (SAR) images to obtain distance and azimuth-oriented displacement velocity.[29] Meanwhile, they also used optical and SAR results to derive three-dimensional glacier displacement velocity and reveal the dynamic mechanism of glacier activity.

3. Discrete element numerical simulation

3.1 Research status

As for river blocking events, most of them take landslide as the research object, and the channel type debris flow is less. Such studies are mainly described after the fact (size, breakout distance, coverage, etc.), and direct monitoring data are lacking. Discrete element numerical simulation is the main technique to study the evolution of debris flow and river blocking. Li Dongyang et al. reproduced the river blocking

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and surge evolution process of Baige landslide on the Jinsha River by using the extended DEM-CFD coupled numerical method proposed by themselves. [34] Du Wenjie et al. reproduced the whole process of landslide blocking Pingdu River in Erhuang Village, Shiyan City, Hubei Province in 2011 through two-phase dual-particle MPM simulation.[35] Cai Yaojun et al. used PFC^{3D} software to simulate the Baige landslide in the upper reaches of the Jinsha River based on the valley topographic data, and combined with the morphological characteristics of the two Baige weir bodies, predicted the deposit patterns of the weir bodies with different instability scales. [36]

With the development of science and technology, the combination of numerical simulation and remote sensing image brings more possibilities for disaster research. Agatova et al. used remote sensing combined with field investigation to analyze the degradation rate of Glacier No. 15 and its nearby glaciers before and after the 1988 Tsambagarav ridge earthquake in Altai, Mongolia based on multi-year image data, and evaluated the impact of earthquakes on reducing "damaged" glaciers under the condition of global warming.[37] Zhang et al. used multi-temporal satellite images to analyze the characteristics and dynamic process of the ice and rock collapse disaster in Chamoli, Himalaya, India in 2021.[38] Westoby et al. combined satellite remote sensing, numerical simulation and field observation to reconstruct the impact of ice avalanch-debris flow on river channels in Chamoli district, Uttarakhand, India, on February 7, 2021. [39]

In recent years, discrete element numerical simulation have become a very mature numerical calculation method in geotechnical engineering fields such as slope engineering, underground cavity excavation, and roadbed stability[40]. Particle Flow Code (PFC) is a discrete element numerical analysis software mainly used to solve various engineering and scientific simulation problems related to particles [41]. Different from finite element simulation, particle flow is more in line with the characteristics of granular materials and has shown certain advantages in the calculation of soil slopes, so it is used by many scholars [42]. PFC can be used for effective inversion of landslide, debris flow, debris flow and other disasters. Cao Wen et al. used PFC5.0 to simulate the redstone landslide triggered by the 2014 earthquake. [43] Chen Luozeng et al. used particle flow discrete element PFC3D software to invert the sliding, debris flow, debris flow accumulation and stopping stages of the high-speed remote landslide, and reproduced the motion process of the high-speed remote landslide in Yigong. [44] Wei et al. used PFC to conduct dynamic analysis of the landslide that occurred in Mabian, Leshan City, Sichuan Province on May 5, 2018.[40] Li, Lo and Tang et al. used PFC to simulate the whole process of landslide-debris body and collapse-debris body blocking river, and obtained a similar rule, that is, the reduction of friction coefficient of sliding bed makes the sliding distance of debris body larger, and the final accumulation body tends to increase in length and decrease in height. [45-47] Zhou et al studied the influence of the strength of the sliding body on the movement and accumulation characteristics of the debris body by using PFC. The lower the strength is, the more the sliding body will break up.[48] Fan Yuanyuan et al. used PFC direct shear test simulation and experiment combined with calibration of relevant parameters calibrate correlation parameter, and then used PFC to numerically simulate the starting of debris flow from moraine source under different moisture content. [49] The PFC can also be coupled with finite element software to achieve more realistic simulations. For example, Chen Wenxiao et al. established a fluid-structure coupling calculation method based on PFC and OpenFOAM, and analyzed the dynamic characteristics and accumulation patterns of underwater landslides.[50]

3.2 Inversion of typical hazards

On the basis of previous studies, the disaster caused by ice and rock collapse/debris flow blocking river in October 2018 in Sedongpu was selected. Based on the measured and investigated data, PFC software and geological model were established (see Figure 1) to carry out full-scale numerical simulation inversion. In view of the huge area of Sitongpugou Basin (about 65 km^2), rich provenance and more than 100 million m^3 of dynamic reserves, the calculation efficiency will be seriously affected if realistic particle size distribution is adopted, so the average particle size (10 m) is adopted here.

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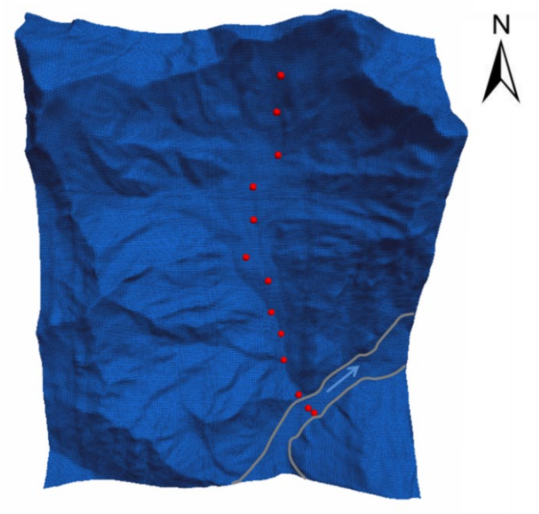

Figure 1: Numerical simulation of geological models

As shown in Figure 1, in the start-up stage, the debris flow movement process was triggered by high ice and rock avalanche particles in the upper watershed. Through the amplification effect of erosion along the channel, a large number of particles in the channel move to the inlet of the main channel of the Yarlung Zangbo River, causing river blocking (see Figure 2).

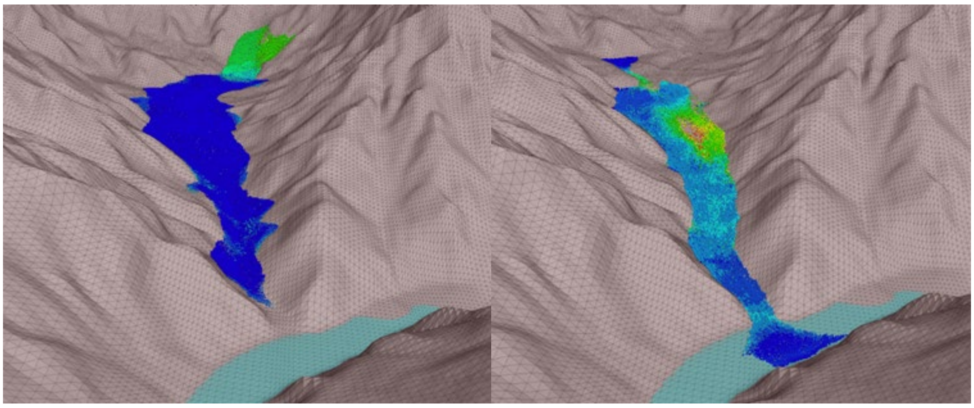

Figure 2: Debris flow disaster process: start-up process (left); River blocking process (right)

Through comparison, the morphological characteristics of the deposition at the confluence between Sedongpu gully and the main river are in good agreement with the real data (see Figure 3). From the comparison of the length, height and volume data of the generalized river blocking body (see Table 1), the error of the numerical simulation inversion results is all lower than 10%, which proves that this discrete element numerical simulation method is adopted.

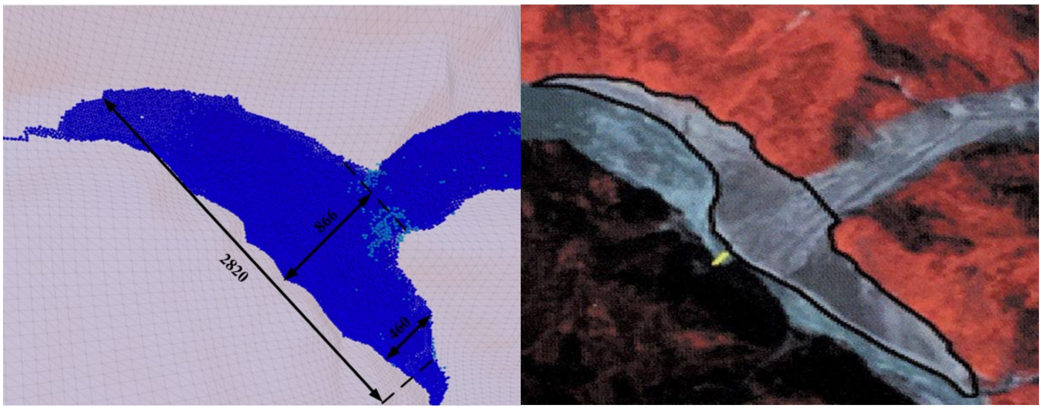

Figure 3: Comparison between inversion and actual morphology: inversion of landslide dam body morphology (left); actual landslide dam body (right)

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Table 1: Comparison of model inversion results with survey estimates

Name		Inversion results	Investigation and evaluation of the calculated value	Error percentage (%)
Characteristics of river blocking body	Length along river(m)	2715	2500	8.60
	Hight (m)	98.7	90	9.67
	Volume ($10^7 m^3$)	6.90	6.6	4.54

4. Conclusion

Based on references study, this paper sorted out the current research progress on glacial avalanche debris flow, which is summarized as follows:

(1) At present, multi-source remote sensing images, DEM, seismic records, meteorological data and other multi-source data are mainly used for analysis, and precipitation, temperature and seismic activity are confirmed as the main factors of disaster.

(2) Numerical simulation and laboratory large-scale model experiment are the main means to analyze the mechanism of debris flow movement of ice avalanche, and relevant research results reveal the physical and mechanical mechanism of ice-rock mixture in the disaster process.

(3) It is a developing trend to use discrete element numerical simulation method to study the motion process of ice avalanche debris flow and the disaster chain process caused by it. This method can overcome the problems such as lack of field monitoring data and scale effect, and analyze the motion induced disaster process from a more detailed perspective.

(4) Using PFC numerical simulation software, the inversion of typical ice and rock collapse debris flow disaster in Sedongpu gully is carried out. The results of virtual inversion are in good agreement with the real situation, which proves the applicability of this kind of research method.

References

[1] Huo M, Wang X, He C, et al. A Preliminary Test Study on Debris Flows in a Contracted Drainage Channel at Mawan Valley, Chongqing [J]. Academic Journal of Environment & Earth Science, 2024, (1), 7-18.
[2] Huo M, Zhou JW, Zhao J, et al. The normal impact stiffness of a debris-flow flexible barrier [J].Scientific Reports, 2023, 13. DOI: 10.1038 / s41598-023-30664-2.
[3] Zhao J, Liu L, Wang, Y.; Tang, K.; Huo, M.; Zhao, Y. Evaluation of sustainable development of the urban ecological environment and its coupling relationship with human activities based on multi-source data [J]. Sustainability, 2023, 15, 4340.
[4] Li D, Liao T, Ruan W, et al. Numerical simulation of morphological evolution in a gravel-bed meandering river during floods: a case study on the Sai-Jiang river [J].Water Science Technology, 2024, 90 (5): 1561–1576.
[5] Yao T D, Xue Y K, Chen D L, et al. Recent Third Pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multi-disciplinary approach with observation, modeling and analysis [J]. Bulletin of the American Meteorological Society, 2019, 100(3): 423-444.
[6] Guo L, Li J, Wu L X, et al. Investigating the Recent Surge in the Monomah Glacier, Central Kunlun Mountain Range with Multiple Sources of Remote Sensing Data[J]. Remote Sensing, 2020, 12(6): 966.
[7] Evan M, Michael M C, Amaury D, et al. Health and sustainability of glaciers in High Mountain Asia[J]. Nature Communications, 2021, 12(1): 2868.
[8] Yin Yueping. A brief discussion on climatic geological hazards in mountainous areas of plateau [J]. Hydrogeology and Engineering Geology, 2004, 31(4): 1.
[9] Hu Wentao, Yao Tandong, Yu Wusheng, et al. Research progress of ice avalanche in High Asia [J]. Journal of Glaciology and Geocryology, 2018, 40(06): 1141-1152.
[10] Yao Tandong, An Baosheng, Xu Xiangde. Scientific Assessment Report on the Great Bend of the Brahmaputra River Ice Collapse and river Blocking Event [R]. Beijing: Science Press, 2022.
[11] Liu Chuanzheng. Sedongpugou slipping-clastic flow barrier lake in Yarlung Zangbo River [J]. The Chinese Journal of Geological Hazard and Control, 2018, 29(06): 7.
[12] Tong Liqiang, Tu Jienan, Pei Lixin, et al. A preliminary study on the frequent occurrence of debris

ISSN 2616-5872 Vol.6, Issue 5: 82-88, DOI: 10.25236/AJEE.2024.060511

flow events in the Garabaifeng Sedongpu flow region of the Yarlung Zangbo River [J]. Journal of Engineering Geology, 2018, 26(06): 1552-1561.

[13] Li Kunzhong, Zhang Mingzhe, Xing Aiguo. Process simulation and motion characteristics analysis of slipping-debris flow in Sedongpugou, Yarlung Zangbo River [J]. The Chinese Journal of Geological Hazard and Control, 2021, 32(01): 18-27.

[14] Cuffer K, Paterson W. The Physics of Glaciers (fourth Edi-tion) [M]. Amsterdam: Academic Press, 2010.

[15] Qin Dahe. Dictionary of Cryosphere Science [M]. Beijing: China Meteorological Press, 2014.

[16] Zhang Ming, Yin Yueping, Wu Shuren, et al. Research status and prospect of high-speed remote landslide-clastic flow mechanism [J]. Journal of Engineering Geology, 2010, 18(06): 805-817.

[17] Liu Chuanzheng. High-speed remote problem of landslides and debris flow [J]. Geological Review, 2017, 63(06): 1563-1575.

[18] Yang Chao. Evolution characteristics and genetic mechanism of glacial debris flow in Sedongpugou, Yarlung Zangbo River [D]. Chengdu, Chengdu University of Technology, 2019

[19] Yang Qingqing, Zheng Xinyu, Su Zhiman, et al. Research progress of high-speed long-range ice-rock clastic flow [J]. Earth Science, 2022, 47(03): 935-949.

[20] Yang Q Q, Su Z M, Cheng Q G, et al. High mobility of rock-ice avalanches: Insights from small flume tests of gravel-ice mixtures [J]. Engineering Geology, 2019, 260(0): 105260.

[21] Yang Yiqing, Su Zhiman, Chen Luozeng, et al. Preliminary analysis of the effect of ice debris on the movement characteristics of ice-rock clastic flow [J]. Chinese Journal of Engineering Geology, 2015, 23(06): 1117-1126.

[22] Ren Y H, Yang Q Q, Cheng Q G, et al. Solid-liquid interaction caused by minor wetting in gravel-ice mixtures: A key factor for the mobility of rock-ice avalanches [J]. Engineering Geology, 2021, 286, 106072.

[23] Sosio R. Landslide Hazards, Risks, and Disasters [M]. Elsevier, 2015: 191-240.

[24] Schneider D, Huggel C, Haeberli W, et al. Unraveling driving factors for large rock-ice avalanche mobility [J]. Earth Surface Processes and Landforms, 2011, 36(14): 1948-1966.

[25] Tang Minggao, Liu Xinxin, Li Guang, et al. Experimental study on mechanism of ice collapse in Sedongpugou, Yarlung Zangbo River [J]. Earth Science Frontiers, 2023, 30(4): 405-417.

[26] Zhang Longyu, Li Sumin, Yu Sunju, et al. Research on pre-disaster deformation in Sitongpu Basin based on SBAS-InSAR and Offset-Tracking [J]. Journal of Geodesy and Geodynamics, 2023, 12(1): 1-14.

[27] Gao H Y, Yin Y P, Li B, et al. Geomorphic evolution of the Sedongpu Basin after catastrophic ice and rock avalanches triggered by the 2017 Ms6.9 Milin earthquake in the Yarlung Zangbo River area, China[J]. Landslides, 2023, 20: 2327-2341.

[28] Zhu Bangyan, Ren Zhizhong, Zhang Qi, et al. Glacier deformation inversion before disaster using SBAS-InSAR technology in Sedongpu basin along the Yarlung Zangbo River [J]. Bulletin of Surveying and Mapping, 2021, (11): 31-35.

[29] Ding C, Feng G, Zhang L, et al. The Precursory 3D Displacement Patterns and Their Implicit Collapse Mechanism of the Ice-Rock Avalanche Events Occurred in Sedongpu Basin Revealed by Optical and SAR Observations [J]. Remote Sensing, 2023, 15(11): 2818.

[30] He C, Liu E L, He S M, et al. On the supraglacial rock avalanches: Thermo-hydro-mechanical analysis considering ice-water phase transition [J]. Geomorphology, 2023, 422: 108550.

[31] Schneider D, Kaitna R, Dietrich W E, et al. Frictional behavior of granular gravel–ice mixtures in vertically rotating drum experiments and implications for rock-ice avalanches[J]. Cold Regions Science and Technology, 2011, 69(1):70-90.

[32] Dong Z B, Su L J. Flow regimes and basal normal stresses in rock-ice avalanches by experimental rotating drum tests [J]. Cold Regions Science and Technology, 2024, 218: 104081.

[33] Huai B J, Ding M H, Ai S T, et al. Glacial Debris Flow Blockage Event (2018) in the Sedongpu Basin of the Yarlung Zangbo River, China: Occurrence Factors and Its Implications[J]. Land, 2022, 11(8): 1217.

[34] Li Dongyang, Nian Tingkai, Wu Hao, et al. DEM-CFD coupling Analysis Method and its application for disaster chain simulation of slippery slope, river blockage and surge [J]. Advanced Engineering Sciences, 2023, 55(01): 141-149.

[35] Du Wenjie, Sheng Qian, Yang Xinghong, et al. Whole process analysis of landslide and river blocking disaster based on two-phase two-particle MPM [J]. Advanced Engineering Sciences, 2022, 54(03): 36-45.

[36] Cai Yaojun, Xu Fuxing, Zhu Meng, et al. Risk analysis of instability of residual body of Baige Landslide in Jinsha River [J]. Engineering Science and Technology, 2021, 53(06): 33-42.

[37] Agatova A, Nepop R, Ganyushkin D, et al. Specific Effects of the 1988 Earthquake on Topography

ISSN 2616-5872 Vol.6, Issue 5: 82-88, DOI: 10.25236/AJEE.2024.060511

and Glaciation of the Tsambagarav Ridge (Mongolian Altai) Based on Remote Sensing and Field Data[J]. Remote Sensing, 2022, 14(4): 917.

[38] Zhang T T, Yin Y P, Li B, et al. Characteristics and dynamic analysis of the February 2021 long-runout disaster chain triggered by massive rock and ice avalanche at Chamoli, Indian Himalaya[J]. Journal of Rock Mechanics and Geotechnical Engineering, 2023, 15: 296-308.

[39] Matthew J. W, Stuart A. D, Jonathan L. C, et al. Rapid fluvial remobilization of sediments deposited by the 2021 Chamoli disaster, Indian Himalaya[J]. Geology, 2023, 51:924-928.

[40] Wei J B, Zhao Z, Xu C, et al. Numerical investigation of landslide kinetics for the recent Mabian landslide (Sichuan, China)[J]. Landslides, 2019, 16: 2287-2298.

[41] Wang Haoran, Wang Yongzhi, Wang Hai, et al. Numerical simulation of PFC~(3D) preparation by sand rain model [J]. Hydro-Science and Engineering, 2021, (04): 68-74.

[42] Ji Xianjun, Liang Ying, Pan Huali, et al. Phase division and analysis of dynamic migration process of viscous debris slope based on PFC~(3D) [J]. Journal of Natural Disasters, 2017, 26(05): 165-173.

[43] Cao Wen, Li Weichao, Tang Bin, et al. Study on 3D modeling method for PFC landslide simulation [J]. Journal of Engineering Geology, 2017, 25(02): 455-462.

[44] Chen Luozeng. Numerical analysis of particle flow in high-speed remote landslide in Yigong [D]. Chengdu, Southwest Jiaotong University, 2016.

[45] Li X P. Simulation of the sliding process of Donghekou landslide triggered by the Wenchuan earthquake using a distinct element method [J]. Environmental Earth Sciences, 2012, 65(4): 1049-1054.

[46] Lo C M, Lin M L, Tang C L, et al. A kinematic model of the Hsiaolin landslide calibrated to the morphology of the landslide deposit [J]. Engineering Geology, 2011, 123(1): 22-39.

[47] Tang C L, Hu J C, Lin M L, et al. The Tsaoling landslide triggered by the Chi-Chi earthquake, Taiwan, China: Insights from a discrete element simulation [J]. Engineering Geology, 2009, 106: 1-19.

[48] Zhou J W, Huang K X, Shi C, et al. Discrete element modeling of the mass movement and loose material supplying the gully process of a debris avalanche in the Bayi Gully, Southwest China[J]. Journal of Asian Earth Sciences, 2015, 99: 95-111.

[49] Fan Yuanyuan, Song Ling, Sun Wen. Simulation of starting process of moraine debris flow based on PFC [J]. Journal of Arid Land Resources and Environment, 2021, 35(03): 140-146.

[50] Chen Wenxiao, Shi Chong, Shan Zhigang, et al. Numerical simulation of underwater landslide based on the coupling method of OpenFOAM and PFC [J]. Journal of Engineering Geology, 2021, 29(06): 1823-1830.