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# A photographic method to identify reservoir geohazards induced by rock mass deterioration of hydro-fluctuation belt

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Potential geohazards triggered by the rock mass deterioration (RMD) of the hydro-fluctuation belt (HFB) in the Three Gorges Reservoir area (TGRA) severely threaten the lives and property of people, it is necessary and urgent to timely identify this kind of potential geohazard. Aiming at this issue, several typical evolution modes of potential RMD-induced geohazards were generalized, and an unmanned aerial vehicle (UAV) photographic method integrating the orthophotography, three-dimensional multi-angle oblique photography and high-precision digital elevation model (DEM) was proposed to early recognize the newly formed potential RMD-induced geohazards. By resolving the problem of poor precision in the orthophotographic images of high steep bank slopes, the proposed method improved the recognition reliability of potential reservoir geohazards in the HFBs. Taking the bank slopes from Zigui County to Badong County as the study area, 116 new potential RMD-induced geohazard sites were identified by the presented approach, including 64 and 52 sites on the left and right bank, respectively. Through field verifications, 17 and 19 sites on the left and right bank were found to be consistent with existing hazards, indicating the effectiveness of the proposed approach in avoiding the false and missing recognitions of potential RMD-induced reservoir geohazards at current levels of knowledge and technology. The study can provide a valuable reference for the early identification of RMD-induced geohazards in reservoir areas.

## KEYWORDS

reservoir bank slope, rock mass deterioration, geohazard recognition, UAV photography, image interpretation

## 1 Introduction

In the Three Gorges Reservoir area (TGRA), periodic reservoir water impoundment and drawdown led to the repeated water-level fluctuations (Yin et al., 2016), causing periodic changes in the geological environment conditions of the bank slopes. These changes have dramatically degraded the structure and the physio-mechanical properties of the rock

masses in the hydro-fluctuation belt (HFB) (Liu et al., 2008; Liu et al., 2009; Deng et al., 2012a; Deng et al., 2012b; Sun and Zhang, 2019).

Since the implementation of the 175 m experimental impoundment in the TGRA in 2008, geological disasters caused by rock mass deterioration (RMD) in the HFB have grown more common (Huang et al., 2018; Tang et al., 2019; Zhang et al., 2022). By now, a series of studies related to the characteristics, mechanisms, consequences and evaluations of the RMD of the HFB have been carried out (Liu et al., 2008; Liu et al., 2009; Liu et al., 2018; Liu et al., 2020; Kang et al., 2019; Huang et al., 2019; Huang et al., 2020a; Huang et al., 2020b; Huang et al., 2021; Yao et al., 2020; Yan et al., 2020; Yin et al., 2020a; Yin et al., 2020b; Wang et al., 2020a; Wang et al., 2020b; Gu et al., 2021), and it is believed that the RMD of the HFB is an emerging adverse factor affecting the stability of the reservoir bank slopes. For instance, the Kamenziwan landslide (Figure 1A), which occurred in Zigui County of the TGRA on 10 December 2019, was a typical rockslide triggered by the RMD of the HFB. This rockslide destroyed a highway for the transportation of 12,300 people lived in nearby areas, and also damaged citrus groves of 90 acres, several water supply and power lines in the town. Fortunately, no casualties were reported in this landslide event owing to the reliable early warning and effective countermeasures (Yin et al., 2020a). Besides, the continuous RMD of the HFB significantly increased the instability risk of emerging and existing dangerous rock masses (e.g., the Jianchuan dong, Banbiyan, Guanmuling, and Huangyanwo dangerous rock masses in the Wuxia Gorge and the Xiling Gorge), severely threatening the safety of water transportation in the Yangtze River and the lives and property of people living in these areas (Zhang C Y et al., 2021; Yin et al., 2022). Taking the Jianchuan dong dangerous rock mass (Figure 1B) as an example, the cumulative displacement of its base has reached 55 mm so far. Once it collapses suddenly, the consequences can be devastating, just like the tragedy that a towering slab of rock broke from a cliff and toppled onto pleasure boaters drifting near a waterfall on the Furnas Lake, Brazil, occurred on 8 January 2022 (Figure 2). According to the video images

and related reports of this catastrophic accident, there were reasons to believe that the long-term continuous RMD of the HFB played a crucial role. Therefore, early identification and warning of potential geohazards in the reservoir bank slopes from the perspective of the RMD of the HFB is highly prioritized and important for the disaster prevention and mitigation.

Conventionally, the geohazards are generally recognized by field mapping, geophysical survey or engineering investigation, and the requirements of manpower, resources, professional experience and abilities in line with the objectives of good accuracy limit their practical application. Now the mainstream methods for the identifications of reservoir geohazards include the remote sensing and photogrammetric techniques, the former mainly includes the terrestrial laser scanning, airborne laser scanning, infrared thermography, ground based synthetic aperture radar, and differential interferometric synthetic aperture radar, and the latter mainly include the aerial photogrammetry and close range photogrammetry. These techniques are capable of obtaining the information on the temporal and spatial distributions, kinematics of potential geohazards (Hervás et al., 2003; Yin et al., 2010; Tofani et al., 2013; Wasowski and Bovenga, 2014; Sun et al., 2015; Dong et al., 2018; Carlà et al., 2019; Macciotta and Hendry, 2021), and their implementations usually need a carrier such as aircraft, spacecraft, terrestrial-based platform, and so on. By utilizing these techniques, even the three dimensional large-scale terrain mappings of the unsafe, inaccessible, or vulnerable areas for investigators can be achieved efficiently and quickly (Oppikofer et al., 2009; Abellán et al., 2014). Due to the revisit period of satellites and the high requirement of professional skills in processing the acquired data, the applicability of these techniques for early recognition of geohazards may be limited. The advantages and disadvantages of these techniques are briefly clarified in the Table 1 (Hervás et al., 2003).

As to the practical application of these techniques in recognition and monitoring of reservoir geohazards, some valuable academic fruits have been achieved through several scholar's attempts

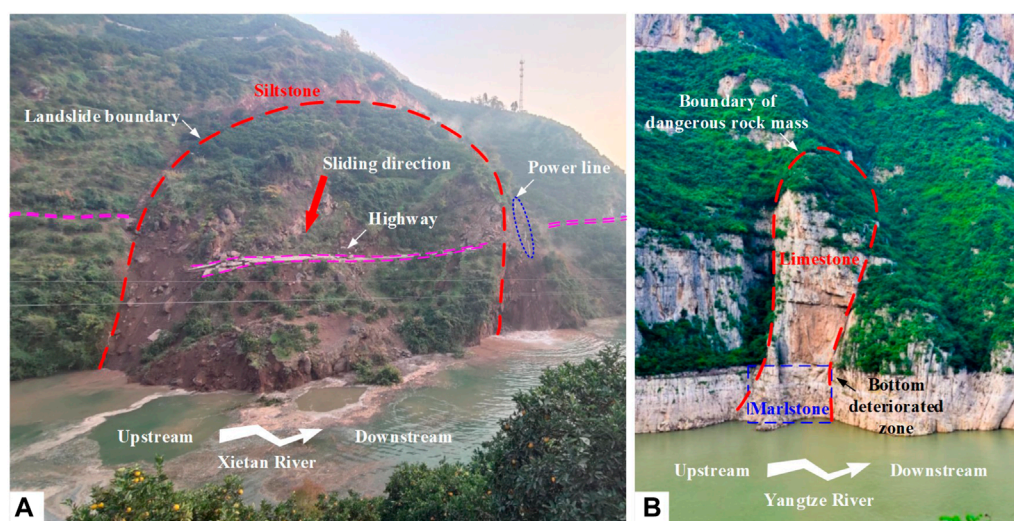
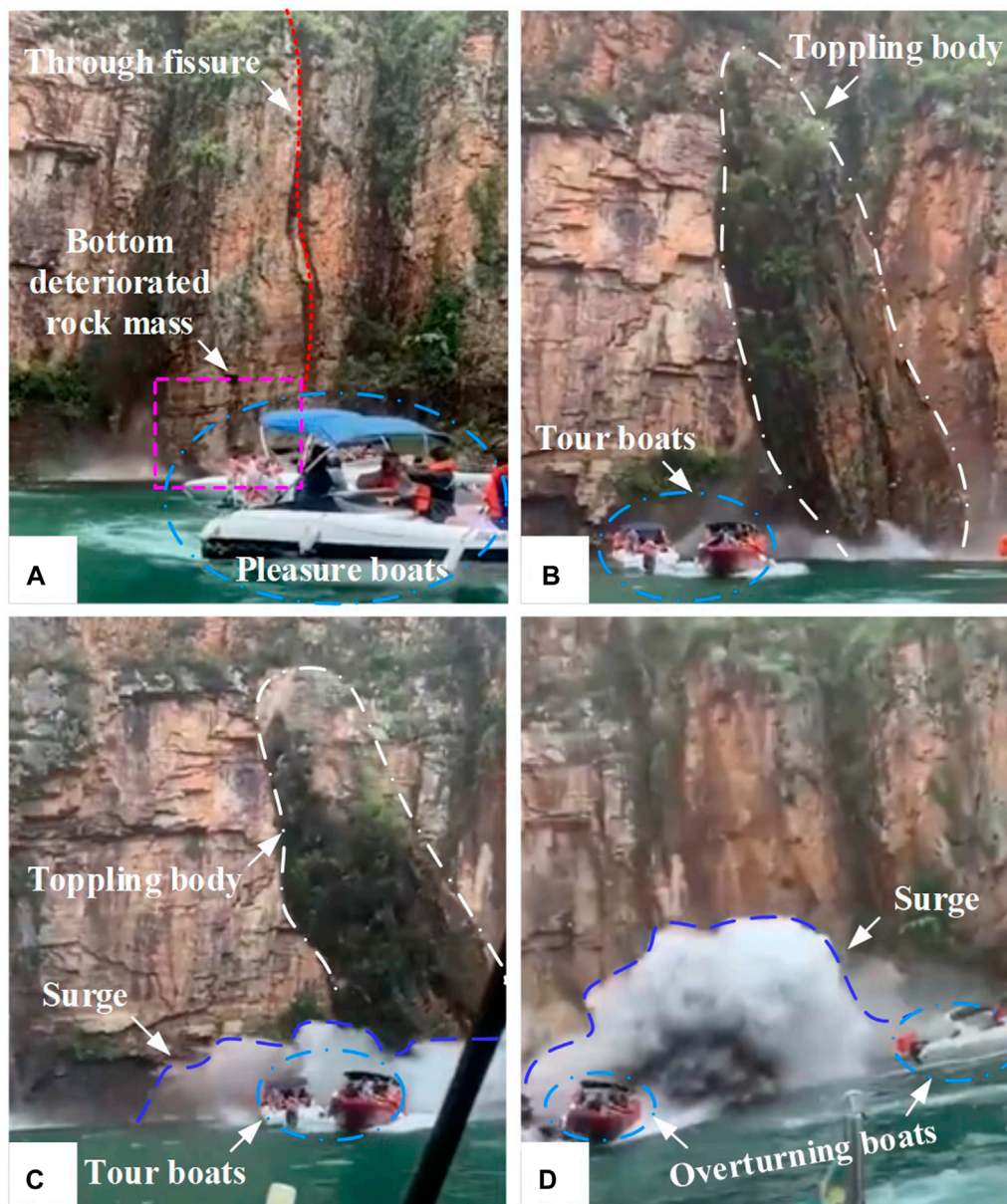


FIGURE 1  
Typical geohazards related to the RMD of the HFB in the TGRA: (A) Kamenziwan landslide; (B) Jianchuan dong dangerous rock mass.





**FIGURE 2**

On January 8, 2022, a massive rock slab detached from a cliff and fell onto leisure boaters floating near a waterfall at Furnas Lake, Brazil. The incident involved the following sequence of events: **(A)** the rock had evidently experienced deterioration, forming a weak area at the base of the slope prior to the collapse; **(B)** the moment the failure was initiated; **(C)** the rockfall generated a powerful surge in the water; and **(D)** the resulting surges led to the boat capsizing.

(Huang et al., 2017; Zhao et al., 2018; Wu et al., 2022; Zhao et al., 2022). For the remote sensing images acquired by most of these techniques, the spatial and temporal resolution are not sufficient to monitor most slope deformation, and the usage of remote sensing still faces challenges in monitoring the steep mountainous slopes whose gradients are greater than  $40^\circ$  (Huang et al., 2017; Dong et al., 2022). For instance, when the direct georeferencing is adapted, large vertical errors often manifest in datasets with vertically oriented objects and extensive vertical landscape features (Nesbit et al., 2022). Owing to the low accuracy and resolution of the remote sensing images for the high steep slopes, the situations of false and missing identifications of potential reservoir geohazards could occur quite

often in practice. Additionally, few attentions have been paid to the reservoir geohazards induced by RMD, not to mention the early recognition of this kind of geohazards.

In this paper, the bank slopes from Zigui County to Badong County in the TGRA were selected as the study objects to establish the generalized evolution modes of typical RMD-induced geohazards. By integrating the orthophotographic imaging, three-dimensional multi-angle oblique imaging, and high-precision digital elevation model (DEM), a new unmanned aerial vehicle (UAV) photographic approach was proposed for early identification of RMD-induced geohazards in the reservoir bank slopes. Its practical application in the field survey indicated the good reliability of the presented method.

TABLE 1 Comparison of different techniques for geohazard recognition.

Technique		Advantage	Disadvantage
Remote sensing technique	Terrestrial laser scanning	It is characterized by three dimensional capabilities, high resolution, good accuracy, and large coverage	It is difficult to operate in rainy or foggy weather conditions, and the data processing requires professionals
	Airborne laser scanning	The accurate digital terrain models for larger areas can be obtained quickly and efficiently	Compared with the terrestrial laser scanning, its accuracy is low
	Infrared thermography	It can be used in the environment of complete darkness, and the resolution is high	Its usage in cold season is restricted
	Ground based synthetic aperture radar	It has the characteristics of high accuracy and resolution, flexibility and versatility	It may lose the coherence, and is difficult in real-time monitoring
	Differential interferometric synthetic aperture radar	It can be used at any time and weather conditions, and its spatial resolution is high	The temporal resolution is relatively low
Photogrammetric technique	Aerial photogrammetry	It is applicable to the unsafe and inaccessible areas for investigators	The image quality is influenced by weather conditions
	Close range photogrammetry	The noncontact operation can be realized and the acquisition rate is high	The image quality is influenced by weather conditions

## 2 Materials and methods

### 2.1 Main types of RMD in HFB in the three gorges reservoir area

After water storage in the Three Gorges Reservoir, the rock masses of HFBs on both banks of the main Yangtze River channel all show different degrees of deterioration. For the HFBs from Zigui County to Badong County, the rock masses of bank slopes with different lithology and structures significantly present different deterioration features under water-rock interaction, water erosion, periodic stress, and environmental load. Through field investigation and data analysis of actual cases depicted in the Figure 3, the RMD of HFBs with carbonate and clastic rocks in the study area mainly includes seven types, i.e., dissolution-suffosion, crack development-extension, mechanical erosion, loosening-spalling, erosion-abrasion, collapsing-block falling near structural planes, and weak strip interlayer denudation, referring to previous related research (Huang et al., 2019; Huang et al., 2020b; Yan et al., 2021).

#### 2.1.1 RMD of carbonate rocks in HFB

##### 2.1.1.1 Dissolution-suffosion

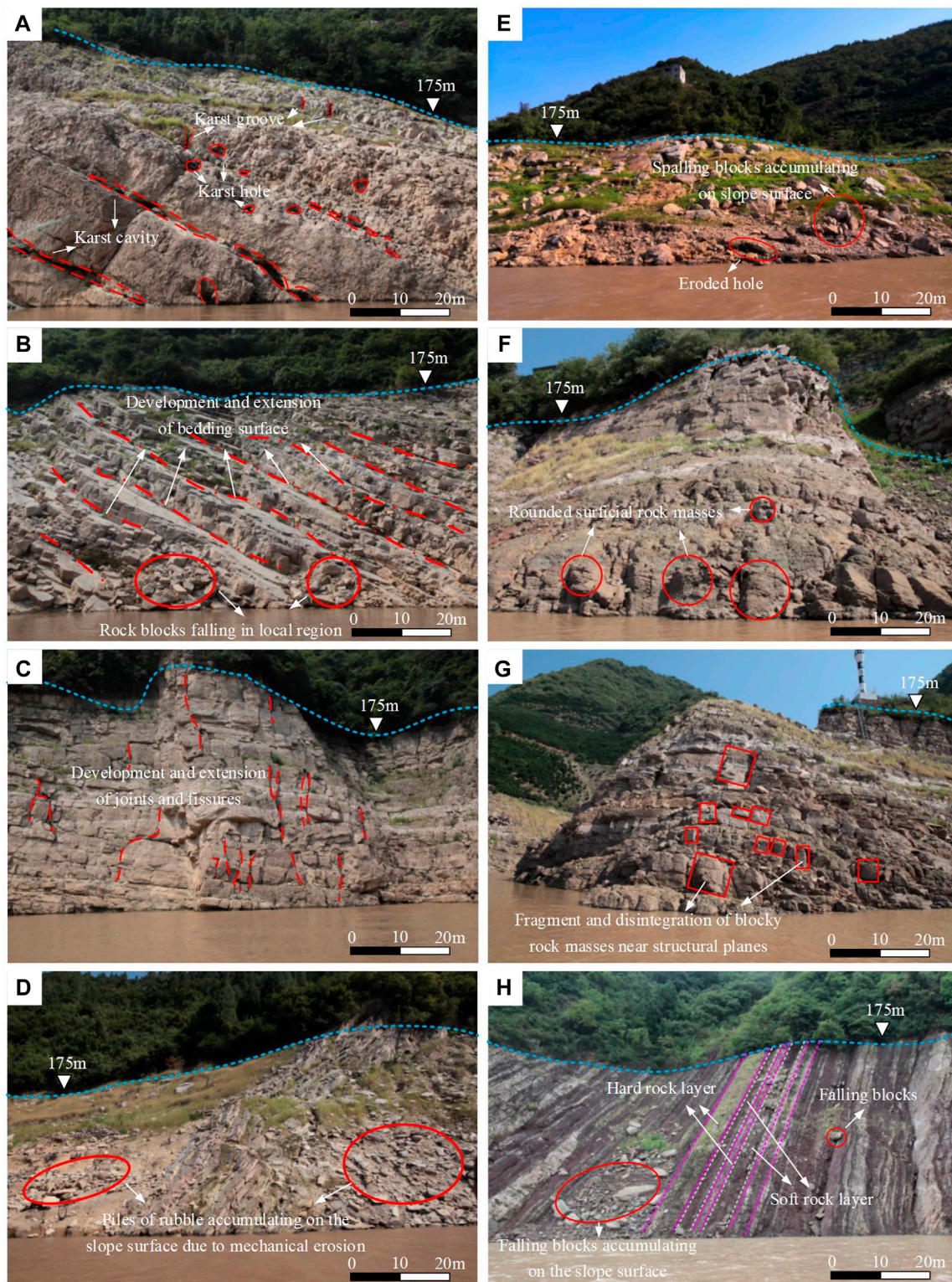
Starting at the beginning of water storage in the Three Gorges Reservoir, the reservoir water level has been fluctuating for a long period of time. The maximum single-day fluctuation amplitudes of the water level of the TGRA from 1 September 2008 to 1 September 2020 can be found in the relevant literature (Dai et al., 2022). The surface water and groundwater near the HFBs of the bank slopes are extremely active, which may lead to subsurface corrosion of the shallow carbonate rocks with joints and fissures. In a large number of gently-dipping stratified carbonate slopes, there are many karst

holes, cavities, and grooves along the joints, fissures and bedding planes of rock masses in the HFBs. For example, due to corroded grooves widely developed along the bank slopes of Zhenjiang Temple, the residual rock barriers between such corroded grooves are as thin as blades, as illustrated in the Figure 3A. The dissolution is a common karst phenomenon reflecting the process of chemical erosion of soluble rocks by water, which can reduce the integrity and quality of the surficial rock masses in the HFBs of the bank slopes. The solubility of rock, the permeability of rock, the corrosion ability of water, and the cyclic alternation of water level are the basic conditions for the development of karst (Wang and Yu, 2018; Huang et al., 2019; Yin et al., 2021). For the most of carbonate HFBs, the near-surface water has the characteristics of weak corrosion due to the dissolution of CO<sub>2</sub> and acidic rainwater, and strong flowability due to the periodic adjustment of reservoir water level, which meets the aforementioned basic conditions required for dissolution. The dissolution process readily occurs in the karst areas of the HFBs of the bank slopes, especially in the structural planes with a little calcium cementation. When the calcareous cement or cementation layer filled in the structural planes and original karst holes is dissolved, the loose particles formed are easily carried away by flowing water, resulting in subsurface suffosion. Thus, this type of RMD can be regarded as the process of dissolution-suffosion.

##### 2.1.1.2 Crack development-extension

For the bank slopes mainly composed of thin to medium layered limestone and dolomite in the study area, the structural planes of rock masses in the HFBs significantly develop, and the surficial bedding planes, joints and fissures gradually emerge and expand due to the periodic change in the reservoir water level, resulting in the deterioration phenomena that the shallow rock masses detach





**FIGURE 3** Typical cases of RMD occurred in the HFBS of the TGRA: (A) dissolution-suffosion (B, C) crack development-extension, (D) mechanical erosion, (E) loosening-spalling, (F) erosion-abrasion, (G) collapsing-block falling near structural planes, and (H) weak strip interlayer denudation.

from the host rock by fracturing or falling. Through a detailed investigation on the development characteristics of structural planes within the HFBS, the consequent and oblique bedding slopes are

characterized by the development and extension of bedding planes (Figure 3B), whereas the reverse and transverse bank slopes are mainly characterized by the development and extension of joints and



(Figure 3C). In addition, compared with the rock mass above the HFBs, the number of fissures within the HFB increases, and the crack width and trace length generally grow, indicating significant deterioration characteristics. The complicated mechanism for the crack development-expansion of rock masses is closely related to the environmental change of surface water and groundwater, the temperature stress, and the hydro-mechanical coupling effect. The jointed rock masses experience stress-corrosion cracking under the combined action of a high ground stress field and slightly corrosive water flow. That is, rock bridges or closed structural surfaces crack or break because their strengths decrease under the long-term stress effect and chemical corrosion. The stress-corrosion cracking generally enables the rock mass to break under a low-medium stress (compared to the normal failure stress state), which is a chemo-mechanical coupling effect.

#### 2.1.1.3 Mechanical erosion

In the study area, small cavities emerge in the local region of weak layers or fissure belts when the fillings of discontinuities within the HFBs of carbonate bank slopes are eroded away by water flow. Then, under the continuous erosion of flowing water, the original joints and fissures in the rock masses further develop and extend towards the cavity. In addition, the mechanical erosion caused by water flow, rainfall, groundwater, and sand-carrying water may also alter the morphology of karst bank slopes (Figure 3D). The mechanical erosion is generally dominated by the impact force and drag force imposed on the surficial loose cataclastic rock masses by water flow, and the degree of erosion can be characterized by the annual erosion amount or erosion rate. In the HFBs of the carbonate bank slopes in the TGRA, the mechanical erosion enables many grooves and cavities to emerge within the rock masses, and eventually leads to a significant change in the original structure of shallow rock masses.

### 2.1.2 RMD of clastic rocks in HFB

#### 2.1.2.1 Loosening-spalling

The clastic rocks in the HFBs of the bank slopes within the study area mainly include argillaceous sandstone and argillaceous shale. They are easy to soften and loosen in contact with water, and then peel off under the erosion of water flow and the gravity, causing the rock masses in the HFBs of bank slopes to loosen and spall. With this type of RMD, the bedrock outcrops peel off, and some rock fragments of various sizes, mainly red purple sandstone, remain on the bank slopes. Besides, there are visible eroded holes and Quaternary deposits in some parts, as illustrated in the Figure 3E. In summer, the temperature of the surficial rock masses in the HFBs can exceed 60°C, and the temperature difference in a day may be more than 25°C. Additionally, the periodic water level adjustment enables the rock masses to experience an immersion and air-drying cycle for a long period of time. The temperature stress generated on the surface and interior of rocks, and the expansion and contraction resulting from the water saturation-dehydration cycling make the surficial rock masses lamellar, sill-like, small block-shaped or scaly so that they crack, loosen, and peel off from the bank slopes.

#### 2.1.2.2 Erosion-abrasion

There are many bank slopes with sandstone-argillaceous shale interbeddings in the study area. These rocks are easy to soften in contact with water, causing rock fragments to fall off and round under

the action of water flow. Erosion-abrasion is characterized by the relatively clean slope surface with less debris, the rounded shallow rock masses dominated by red purple sandstone, the visible corroded holes and the Quaternary deposits in the local region (Figure 3F). The process of erosion-abrasion mainly refers to the combined action of impact and abrasion between the debris carried by water flows or waves and the bedrock surface. Therefore, when the rock masses in the HFBs have undergone erosion-abrasion, the slope surface is very clean, and parts of the shallow rock masses are rounded.

#### 2.1.2.3 Collapsing-block falling near structural planes

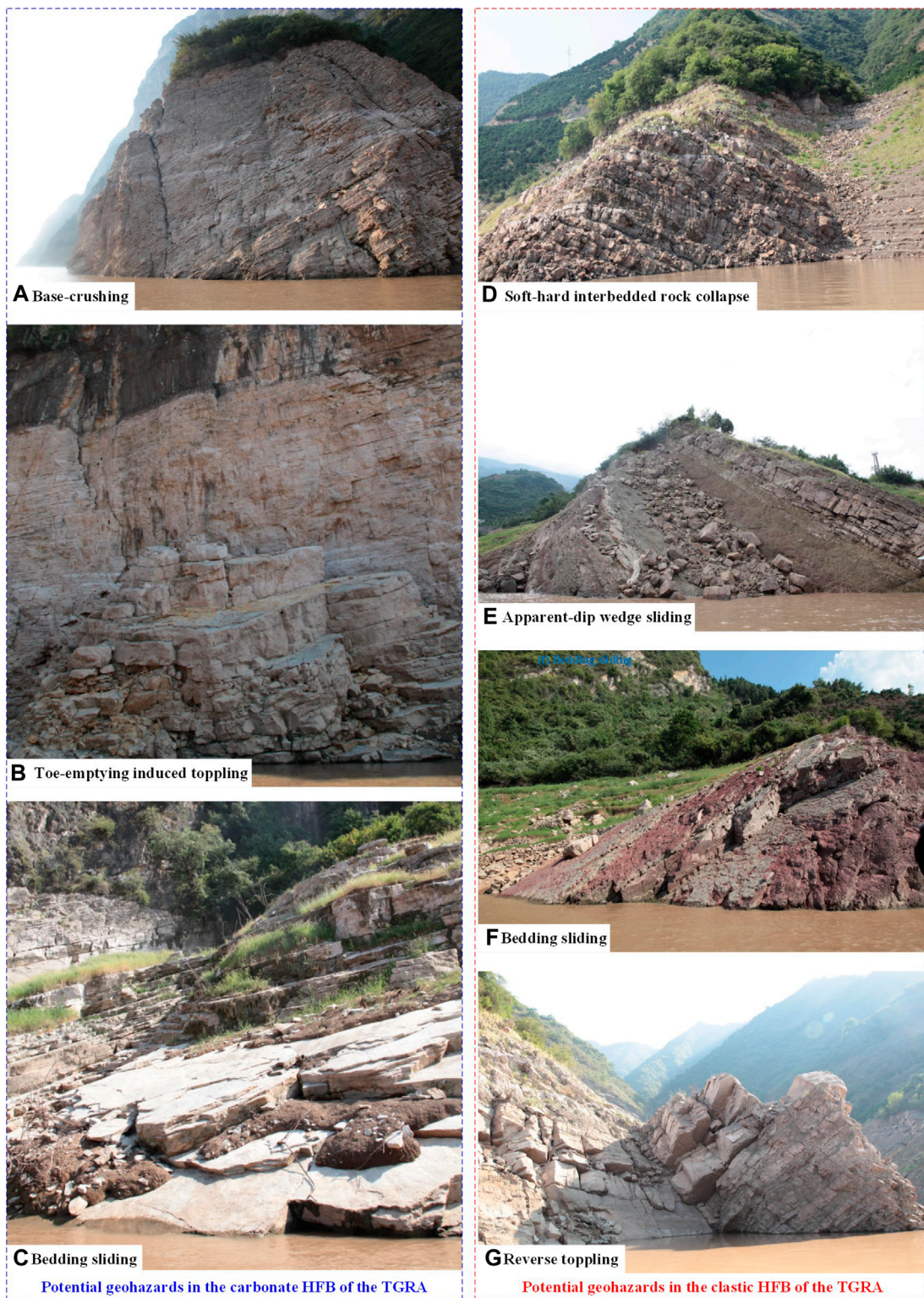
The HFBs of sand-shale interbeddings within the study area readily hollows out under the action of water flow, resulting in the fragment and disintegration of medium layered sandstone along the original structural planes. As to this type of RMD, a large number of unloading fissures emerge on the bank slope surface, mainly consist of two group of primary structural planes. One group of structural planes are roughly parallel with the bank slope surface, while the other group is nearly perpendicular to the bank slope surface. Most of the rocks are red purple sandstone, and many of them hang on the slope surface, forming a “tofu-like” shape, and readily fall off (Figure 3G). During the process of collapsing-block falling near structural planes, after the shallow rock masses in the HFBs become loose and corroded, the soft rock layers are hollowed out, and the local concentrated stress in the rock masses causes the fissures to expand and further results in the cracking and disintegration of rock blocks.

#### 2.1.2.4 Weak strip interlayer denudation

Many bank slopes in the study area are dominated by bedding structures, and the alternating soft and hard rock layers are exposed in the HFBs. In particular, the hard rocks are mainly brittle rocks, such as marl, calcareous sandstone, and feldspathic quartz sandstone. The soft rocks mainly include mudstone, siltstone, and shale that have a low strength. For these consequent bedding slopes, the slopes are generally steep, and red purple rock masses often alternate with grey green ones. The exposed rock masses in the HFBs are mainly the sandstone-shale interbeddings. As to the type of weak strip interlayer denudation, the shale as the interlayer of hard rocks firstly softens in water, then it is hollowed out and denuded under the erosion of water flow, causing the thin to medium-thick sandstone or limestone to fall off along the bedding planes. This type of RMD is characterized by the relatively clean slope surface with less debris, and much shale has become soil or soil-like (Figure 3H). The red-purple sandstone readily falls from the host rock when it is struck by a geological hammer. Generally, this type of RMD shows different degrees of erosion; the soft rocks tend to be loosened and eroded, while the hard rocks always experience cracking and disintegration.

## 2.2 Evolution modes for typical RMD-induced geohazards

According to field investigation and existing research fruits (Zhang P et al., 2021), there are several kinds of typical RMD-induced potential reservoir geohazards, including base-crushing, toe-emptying induced toppling, bedding sliding in carbonate bank slopes, and soft-hard interbedded rock collapse, apparent-dip wedge

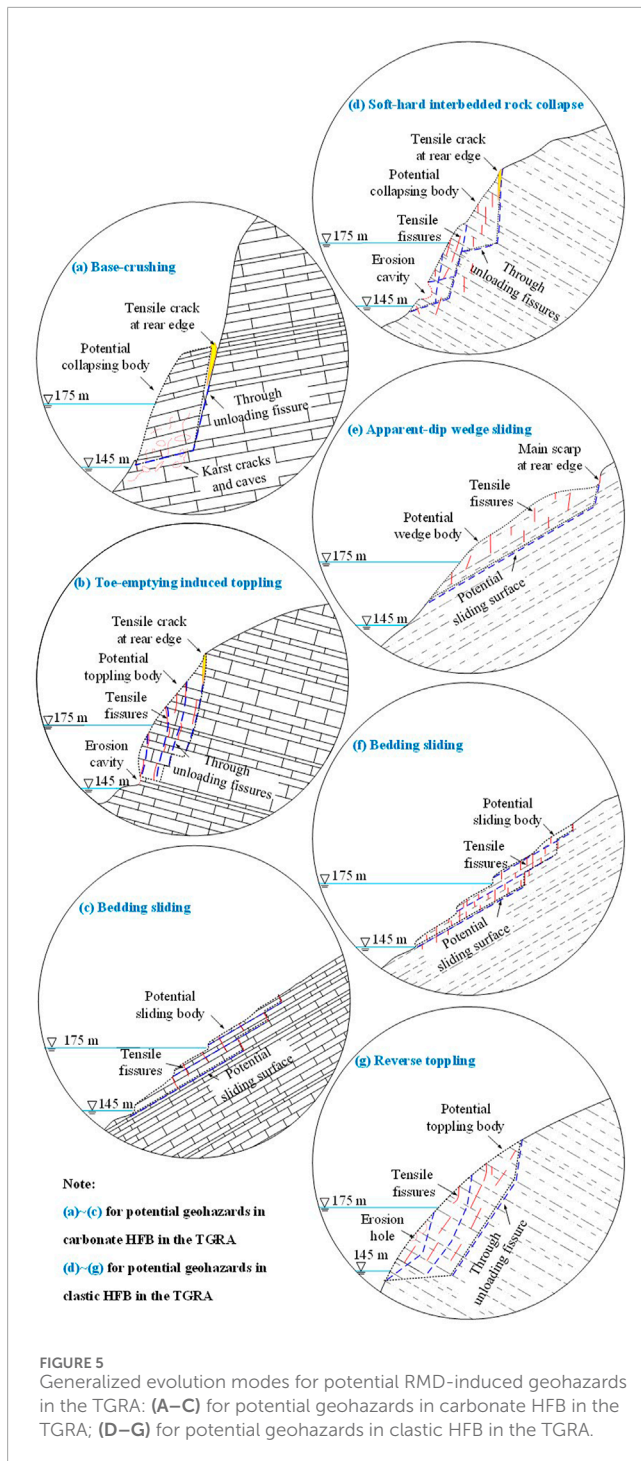


**FIGURE 4** Typical cases of potential RMD-induced geohazards in the TGRA: (A) base-crushing; (B) toe-emptying induced toppling; (C) bedding sliding; (D) soft-hard interbedded rock collapse; (E) apparent-dip wedge sliding; (F) bedding sliding; (G) reverse toppling.

sliding, bedding sliding and reverse toppling in clastic bank slopes, as illustrated in the Figure 4. In combination with the previous descriptions on the types of RMD in the HFBs, the generalized

evolution modes (with seven subcategories) for the potential RMD-induced reservoir geohazards in the TGRA can be established, as depicted in the Figure 5.





## 2.2.1 Evolution modes for RMD-induced geohazards in carbonate bank slopes

### 2.2.1.1 Base-crushing

Bank slopes composed of carbonate rocks are susceptible to karst geological processes, such as the dissolution and suffosion. Under the long-term hydrodynamic environment and the periodic fluctuation of water level, the HFB of the carbonate bank slope, namely, the potential base of unfavorable geological body, can develop many karst ditches, grooves, cracks, and caves. When subjected to intense rainfall or other

external forces, the upper rock masses continue to squeeze the base and gradually disintegrate along the corrosion cracks and unloading fissures, eventually resulting in the occurrence of geological disasters such as collapses or landslides. Figure 5A illustrates the schematic of this potential evolution mode, which usually emerges in the columnar dangerous rock masses with generally small development scales.

### 2.2.1.2 Toe-emptying induced toppling

Under the action of long-term mechanical erosion, such as the erosion and denudation of reservoir water, the relatively weak rock masses in the HFBs of counter-tilt carbonate bank slopes are exposed to a continuous process of drying-wetting cycling, softening, argillization and disintegration. The process contributes to the formation of erosion cracks and cavities with different shapes in the HFBs, which gradually empties the toe of the bank slope. Without the sufficient support, the unloading-induced tensile fractures begin to appear, toppling failure of the upper rock masses finally occurs. Figure 5B depicts the schematic for the potential evolution mode of toe-emptying induced toppling. This failure mode mainly exists in unstable counter-tilt bank slope and slightly occurs in dangerous rock mass, which is usually small-scaled and mostly dustpan-shaped.

### 2.2.1.3 Bedding sliding

Consequent and oblique bedding carbonate bank slopes are widely distributed in the study area. Under the long-term fluctuation of water level, the rock masses in the HFBs continually degrades owing to the erosion, scouring, dissolution and suffosion. The infillings of discontinuities are gradually washed away, and a great number of joint fissures perpendicular to the bedding surfaces emerge continuously in the HFBs due to stress adjustment, which finally cut the massive intact rock into discrete small blocks. Subsequently, the small rock blocks become unstable owing to their gravities and the wave erosion, and begin to slip towards the reservoir along bedding surfaces. The schematic diagram for the bedding sliding mode is provided in the Figure 5C.

## 2.2.2 Evolution modes for RMD-induced geohazards in clastic bank slopes

### 2.2.2.1 Soft-hard interbedded rock collapse

In the study area, there exists many bank slopes with interbeddings of soft and hard rocks, such as the sandstone interbedded with mudstone or shale. Under the action of long-term water-level fluctuation, the interlayered hard rocks fracture and fragment due to the softening and unloading of soft rocks in the HFBs. Subsequently, the joints and fissures continually extend, and finally form the persistent unloading fissure perpendicular to bedding planes. Once the deformation and instability of rock masses separated by highly developed fissures occur in a local steep area, the instable rock masses begin to collapse and slip towards the reservoir. This evolution mode is mainly found in steep zone of counter-tilt bank slopes with interbeddings of soft and hard rocks, and the Figure 5D depicts the corresponding schematic diagram.

### 2.2.2.2 Apparent-dip wedge sliding

Owing to the long-term hydro-fluctuation, the rock masses (siltstone and mudstone) in the HFBs of apparent-dip bank slopes deteriorate dramatically in the alternating dry-wet environment. After



RMD of the anti-slide body at the front edge of the bank slope, a wedge-shaped sliding surface gradually appears in the rear edge, and then extends through the bank slope, which finally leads to the overall wedge sliding of potential unstable rock masses. This kind of rock slide is usually characterized by larger scale, higher starting speed and considerable run-out distance. For instance, the Kamenziwan landslide occurred in Xietan Town, Zigui County, China, on 10 December 2019, is in an apparent-dip wedge sliding mode (Yin et al., 2020a). The schematic diagram of this evolution mode is presented in the Figure 5E.

### 2.2.2.3 Bedding sliding

Due to the scouring, erosion and denudation effects of water on the HFBs of clastic bank slopes, the superficial completely and intensely weathered rock masses of consequent bedding slopes are washed away by water flow, causing the eroded and denudated bank slopes to retreat slowly. The shear strengths of interlayered or superficial weak layers decrease progressively, resulting that the shallow rock masses of HFBs become unstable and then slips towards reservoir along bedding surfaces. In this failure mode, the local and shallow rock masses slide firstly, and then cut the slope toe to form free faces, which might finally lead to a large-scale bedding sliding of upper rock masses. This is a typical evolution mode of newly formed clastic geohazard in the study area. Its schematic is given in the Figure 5F.

### 2.2.2.4 Reverse toppling

As a result of long-term water-level fluctuation, the clastic rock masses in the HFBs of reverse bank slopes are subjected to severe deterioration, and the persistent unloading fissures perpendicular to the bedding surface gradually develops, which splits intact rock into discrete blocks. Once the deformation and failure of discrete rock blocks emerges in a local steep area, the local unstable rock masses collapse and topple towards the reservoir. The reverse toppling mode mainly occurs in steep clastic bank slopes, as depicted in the Figure 5G.

## 2.3 Indices and method for identifying RMD-induced geohazards

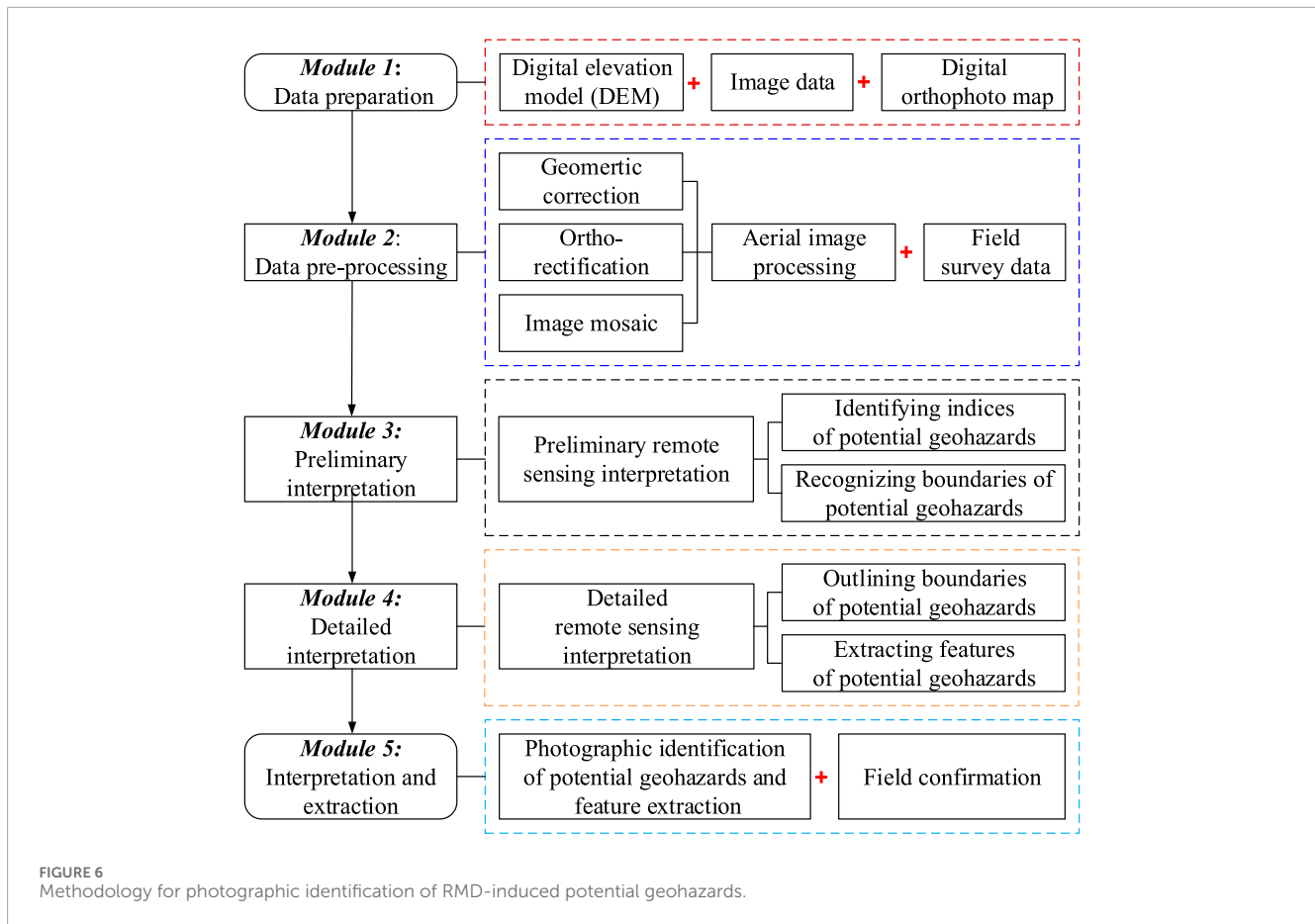
### 2.3.1 Identifying indices for RMD-induced potential geohazards in HFB

This study focuses on the potential geohazards triggered by the RMD of carbonate and clastic HFBs. The proposed evolution modes of geohazards in HFBs are not only influenced by the types of RMD, but also related to other external and internal factors. Thus, the determination of interpretation indices for different evolution modes of RMD-induced geohazards is crucial to identifying potential hazardous sites. With regard to the establishment of the indices of RMD, there are currently no relevant international or national standards available, because the research topic of the RMD of HFBs in the TGRA is somewhat controversial and still in the ascendant. Thus, this paper proposes the qualitative indices of RMD through analysing and summarising the results of the field investigation with reference to the existing research fruits (Huang et al., 2019; Huang et al., 2020a; Huang et al., 2020b; Huang et al., 2021; Yan et al., 2020). The identification process is a technical mean to obtain relevant information on potential geohazards using the human-machine interactive visual interpretation. The principle of this method is

to recognize differences in color tone, shape, shadow, and texture between potential geohazard sites and their background geological bodies. Meanwhile, the types and characteristics of the RMD in the HFBs are also fully considered in the above identification process. In general, interpretation indices refer to the image characteristics contributing to the recognition of the existence, attribute and mutual relationship of the target objects or phenomena, which can be divided into direct and indirect indices. For example, the type of RMD and the development feature of structural plane are regarded as direct interpretation indices. Indirect interpretation indices reflect the properties of a certain object or natural phenomenon, which are internal relations, e.g., the landslide landform, the structure of bank slope, the type of rock strata, the vegetation development, etc. Herein, the interpretation indices of RMD-induced reservoir geohazards are selected based on the consideration of the extrinsic factors triggering the instability, the intrinsic factors controlling the failure mode, and the visible signs reflecting the evolution process of geohazards. Specifically, the triggering factor of reservoir geohazards is water-induced RMD, which can be indirectly reflected by the development of vegetation and directly recognized by the enhancement of macroscopic defects of rock masses. The controlling factors mainly consist of the geomorphological feature, the structure of bank slope, the type of RMD related to the lithology and the structure of rock masses, and the feature of structural plane. The visible signs for the evolution state of potential reservoir geohazards which can be captured by the photographic method are boundary characteristics. The specific interpretation indices for RMD-induced reservoir geohazards in the HFBs and the corresponding descriptions are given in the Supplementary Table SA1.

### 2.3.2 Identification method of RMD-induced potential geohazards

In order to identify the RMD-induced reservoir geohazards by photographic approach, the three-dimensional high-precision DEM of the HFBs is firstly established based on the aerial images obtained by the UAV photography. The raw image data is imported into the Pix4Dmapper to check out the integrity and the light-shade difference of successive images, and whether the overlapping area of the adjacent images is sufficient. The report for the fast processing of the raw data can be used to verify its reliability and high quality. After the raw data meet the quality requirement, the three-dimensional data set can be obtained by aerial triangulation. Then, the original aerial photos are imported into the software smart3D to reproduce the position of every shots according to the longitude, latitude, height and angle of every photos. The relationships among points are established via the smart3D, and the recognized points are included in the intensive computation to generate the greyscale point cloud. By utilizing the internal algorithm for vector function in the smart3D, the point cloud data is transformed into the irregular triangulation network, and further to build the three-dimensional model composed of points, line, and surfaces. The depth maps with different perspectives are matched in a same coordinate system to generate the complete geometric model of the HFBs by image fusion. Later, the mapping relationship between the depth maps and the texture maps is determined, the whole texture mapping map is obtained by texture fusion based on a mixed weight. Finally, the real high-precision three-dimensional model of the HFBs is constructed by texture mapping. After that, the RMD-induced potential geohazards can be identified according



to the established evolution modes considering main interpretation indices. The identification methodology is outlined in the Figure 6.

Specifically, in combination with ArcGIS geographic information system software, ENVI remote sensing software is utilized to process and analyze geospatial imagery obtained by the UAV photography. This image processing consists mostly of geometric correction, ortho-rectification, and image mosaic. At the same time, the DEM is used to classify the inclinations of bank slopes to improve the reliability of interpretation, and to recognize the interpretation indices of potential geohazards according to topography, geomorphology and image characteristic. The above process yields the identification and interpretation results, which includes basic characteristics of potential geohazards, such as morphology, scale, range and distribution.

## 2.4 Recognition of potential RMD-induced geohazards and corresponding evolution modes

For the RMD-induced geohazards in the TGRA, the phenomena of RMD within the HFBs are very common, and the geomorphological characteristic of bank slopes and valleys along the Yangtze River are basically the same. Thus, the interpretation indices of the lithology, rock mass structure, RMD's type, bank slope structure, feature of structural plane, and boundary characteristics given in the Supplementary Table SA1 are sufficient to establish a

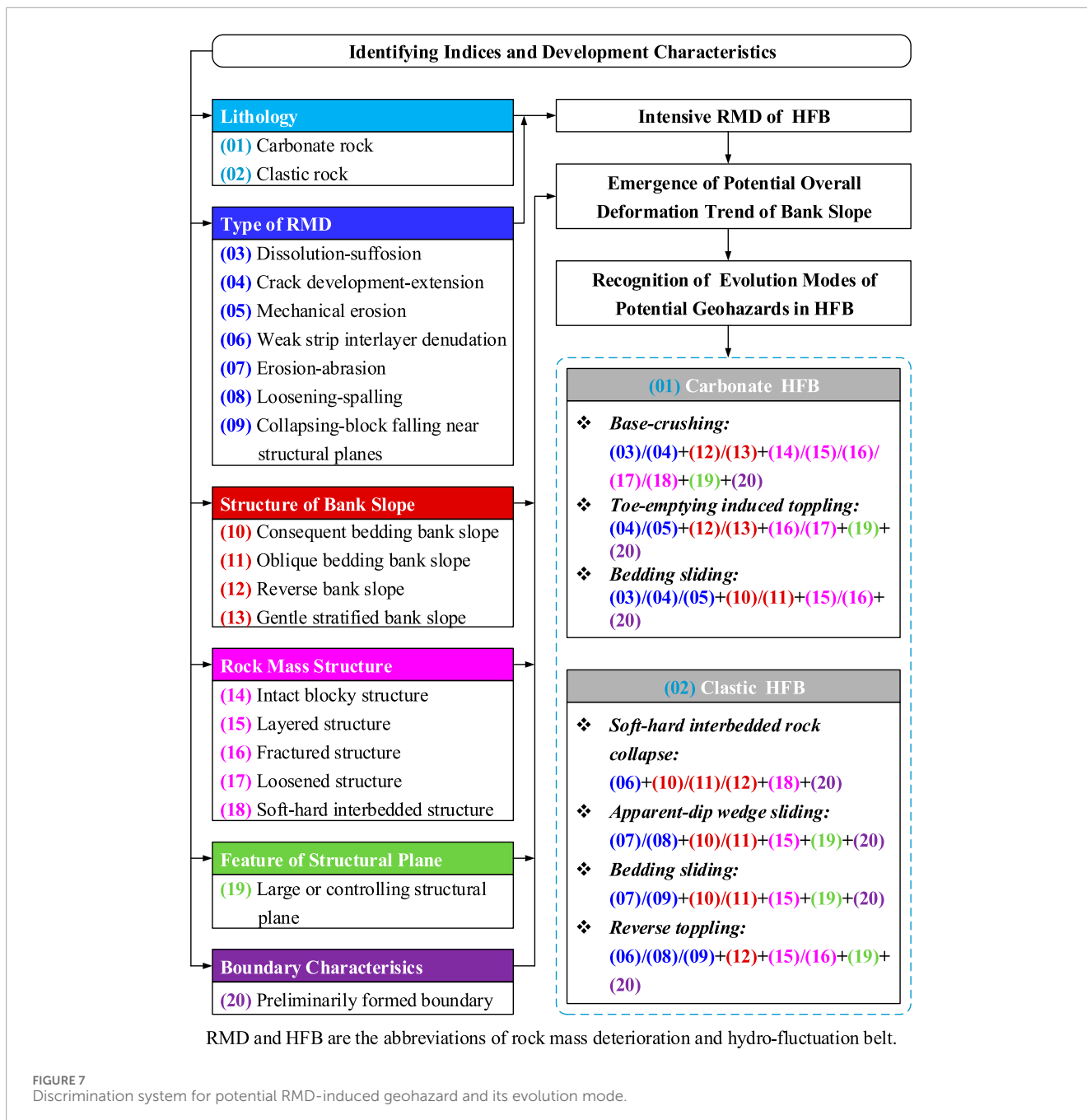
discrimination system for recognition of the potential RMD-induced reservoir geohazards with different evolution modes, as depicted in the Figure 7. Specifically, for the identification of RMD-induced geohazards in the investigated area, the determination of the type of RMD according to the lithology of the HFB is the first step. Then, it is necessary to judge whether the bank slope has a trend of overall deformation or displacement by comprehensively considering the degree of RMD, bank slope structure, rock mass structure, feature of structural plane and boundary characteristics. Eventually, the potential evolution mode of the identified RMD-induced geohazard also can be ascertained based on the generalized models in the Figure 5.

### 2.4.1 Discrimination conditions for potential RMD-induced geohazards in carbonate bank slopes

As depicted in the Figure 7, the discrimination conditions for three typical evolution modes of potential RMD-induced reservoir geohazards in carbonate HFBs are as follows.

#### 2.4.1.1 Base-crushing

The dissolution-suffusion and crack development-extension are the main types of RMD. The large or controlling structural planes have extended into the boundaries of the potential geohazard. The bank slope structures are mainly the reverse or gentle stratified slopes, and the lithology is carbonate rock, e.g., limestone, dolomitic limestone,



and dolomite. Most rock masses are characterized by the columnar shape of intact blocky structure, layered structure, fractured structure, loose structure, or soft-hard interbedded structure. There is little or no vegetation coverage, and the boundaries of potential dangerous rock masses are preliminarily formed.

#### 2.4.1.2 Toe-emptying induced toppling

The crack development-extension and mechanical erosion are the main types of RMD. The large, steeply out-dipping or controlling structural planes are developed. Most slopes are in reverse or gentle stratified structures, and the lithology is hard carbonate rock, such as limestone, dolomitic limestone and dolomite. Most deteriorated rock

masses of HFBs are in fractured or loose structures, and the overlying rock masses are mostly in blocky or layered structures. There is little or no vegetation, and the boundaries of potential dangerous rock masses have preliminarily taken shape.

#### 2.4.1.3 Bedding sliding

The dissolution-suffosion, crack development-extension and mechanical erosion are the main types of RMD. Most bank slopes are in consequent or oblique dipping structures, and the lithology is hard carbonate rock, such as limestone, dolomitic limestone and dolomite. Most rock masses are in intact blocky structure, layered structure or fractured structure. The bedding planes, soft interlayers



or relatively soft layers are quite developed. There is little or no vegetation, and the boundaries of potential landslide hazards have preliminarily taken shape.

## 2.4.2 Discrimination conditions for potential RMD-induced geohazards in clastic bank slopes

Similarly, the conditions for discriminating four typical evolution modes of potential RMD-induced reservoir geohazards in clastic HFBs are as follows (see the [Figure 7](#)):

### 2.4.2.1 Soft-hard interbedded rock collapse

The weak strip interlayer denudation is the major type of RMD in the HFBs, and random structural planes are developed. The slopes are mainly in consequent bedding, oblique bedding or reverse structures, and the lithology is clastic rock, such as interbedded sandstone-mudstone and sandstone interbedded with mud shale. Most of rock masses are in soft-hard interbedded layered structure. There is little or no vegetation, and the boundaries of potential landslide hazards have preliminarily taken shape.

### 2.4.2.2 Apparent-dip wedge sliding

The erosion-abrasion and collapsing-block falling near structural planes are the main types of RMD. The large or controlling structural planes are developed. The slopes were mainly in consequent bedding and oblique bedding structures, and the lithology is clastic rock, such as sandstone, mudstone, shale, interbedded sandstone-mudstone or sandstone interbedded with mud shale. Most of rock masses are in layered structure with soft interlayers or mudstone layers occasionally. The vegetation is not developed well, and there are preliminary boundaries of the potentially landslide hazards.

### 2.4.2.3 Bedding sliding

The main types of RMD, development situation of large or controlling structural planes, structure of bank slopes and the lithology for bedding slide mode are the same as those for the apparent-dip wedge sliding mode. As to the structure of rock masses, layered structure with soft interlayers are fairly common. Additionally, the vegetation is not developed well, and the boundaries of potential landslide hazards have started to form.

### 2.4.2.4 Reverse toppling

The weak strip interlayer denudation, loosening-spalling and collapsing-block falling near structural planes are the main types of RMD. The large and medium-sized structural planes, or controlling structural planes are developed. Most bank slopes are of the reverse structure, and the lithology is clastic rock, such as sandstone, mudstone, shale, interbedded sandstone-mudstone or sandstone interbedded with mud shale. Most rock masses are in layered or fractured structures. The vegetation is not developed well, and the boundaries of potentially landslide hazards have started to take shape.

## 3 Results

### 3.1 Potential geohazards in the study area by the proposed method

Using the presented photographic interpretation method, the spatial coordinates of potential RMD-induced geohazards emerged

in the HFBs of the study area were determined according to the UAV aerial images. It should be clarified that the determination of the RMD's type and range was a prerequisite for the recognition of potential RMD-induced reservoir geohazards in this study. As the detailed field survey indicated that the RMD of same type usually emerged with a certain range, the lines with different colors were selected to divide the HFBs into small segments, whose lengths represented the ranges of the RMD with a specific type. Besides, the ranges of soil bank slopes and treated bank slopes were also delineated in the figures of interpretation results. The long-term effect of water level changes on the soil bank slopes might also lead to reservoir geohazards, but this kind of geohazards were not the concern of this study. As illustrated in the [Figure 8](#), a total of 116 geohazards were identified, including 64 sites on the left bank and 52 sites on the right bank, respectively. And the development characteristics of each reservoir geohazard site were listed in the [Supplementary Table SB1](#).

Additionally, the remote sensing software ENVI 5.3 and the geographic information system software ArcGIS 10.2 were combined to process and analyze the high-precision UAV orthophotographic images, and the boundaries of potential reservoir geohazards were obtained through the human-machine interactive visual interpretation, as depicted in the [Figure 9](#). The development scale and area were also given in the [Supplementary Table SB1](#).

### 3.2 Field verification of interpretation results

In an effort to assess the reliability, quality, and confidence of human-machine interactive visual interpretation outcomes, a field survey was conducted. The survey involved three primary tasks: verifying interpretation indices for various geohazards, conducting field surveys in key areas with unclear attributes, and performing field verifications for randomly selected geohazard sites to evaluate interpretation reliability. The survey methodology entailed route-based observations and fixed-point inspections, focusing on geohazards in key areas, main towns, and along major traffic arteries. Observations were recorded through detailed descriptions and photographic documentation, followed by a comparison with preliminary interpretation results.

The survey findings revealed that the identified potential geohazards on both banks were consistent with existing geohazard sites, demonstrating the effectiveness of the proposed photographic method in avoiding false and missing recognitions of potential RMD-induced reservoir geohazards, given the current state of knowledge and technology. Furthermore, the interpretation results pertaining to landslide types, scales, and morphologies were found to be reasonable. A comprehensive overview of the verification results can be found in [Supplementary Table SB1](#).

### 3.3 Case study of field verified RMD-induced geohazard

Among those verified RMD-induced reservoir geohazards in the [Supplementary Table SB1](#), the Yangjiaping landslide ([Figure 10](#)) is a typical soft-hard interbedded rock collapse. The Yangjiaping landslide lies in the Xietan Town, Zuigui County, Hubei Province, China,

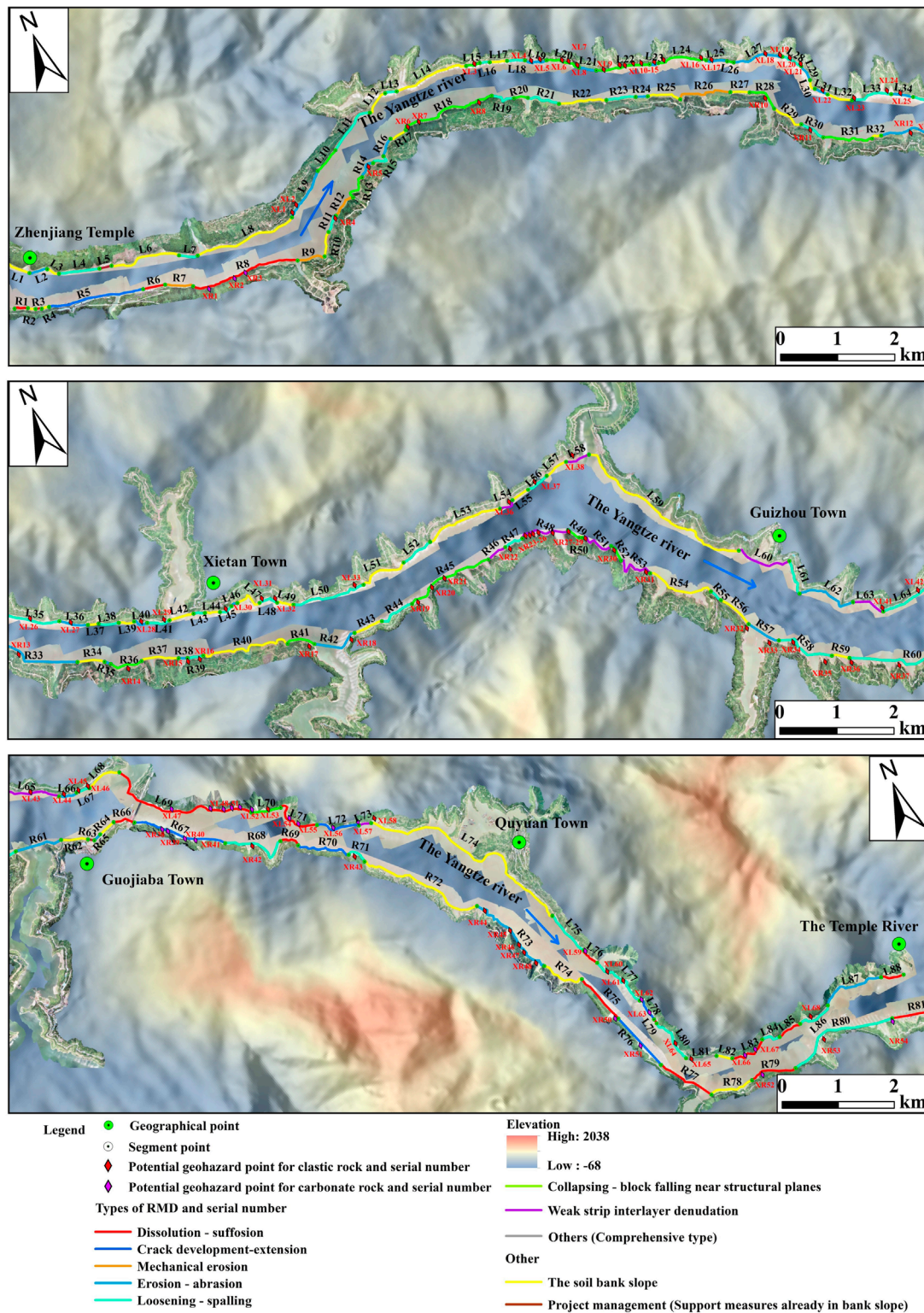


FIGURE 8 Spatial distribution of potential geohazards in the study area.

located on the north bank of the Yangtze River and the left bank of the Xietan River, is about 55 km away from the Three Gorge Dam. This landslide has a dustpan shape on the plane, as shown in the aerial

picture (Figure 10). The front and back widths of the landslide are approximately 130 m and 135 m, respectively. The elevations of the front and rear edges of the landslide are 145 m and 194 m, respectively.



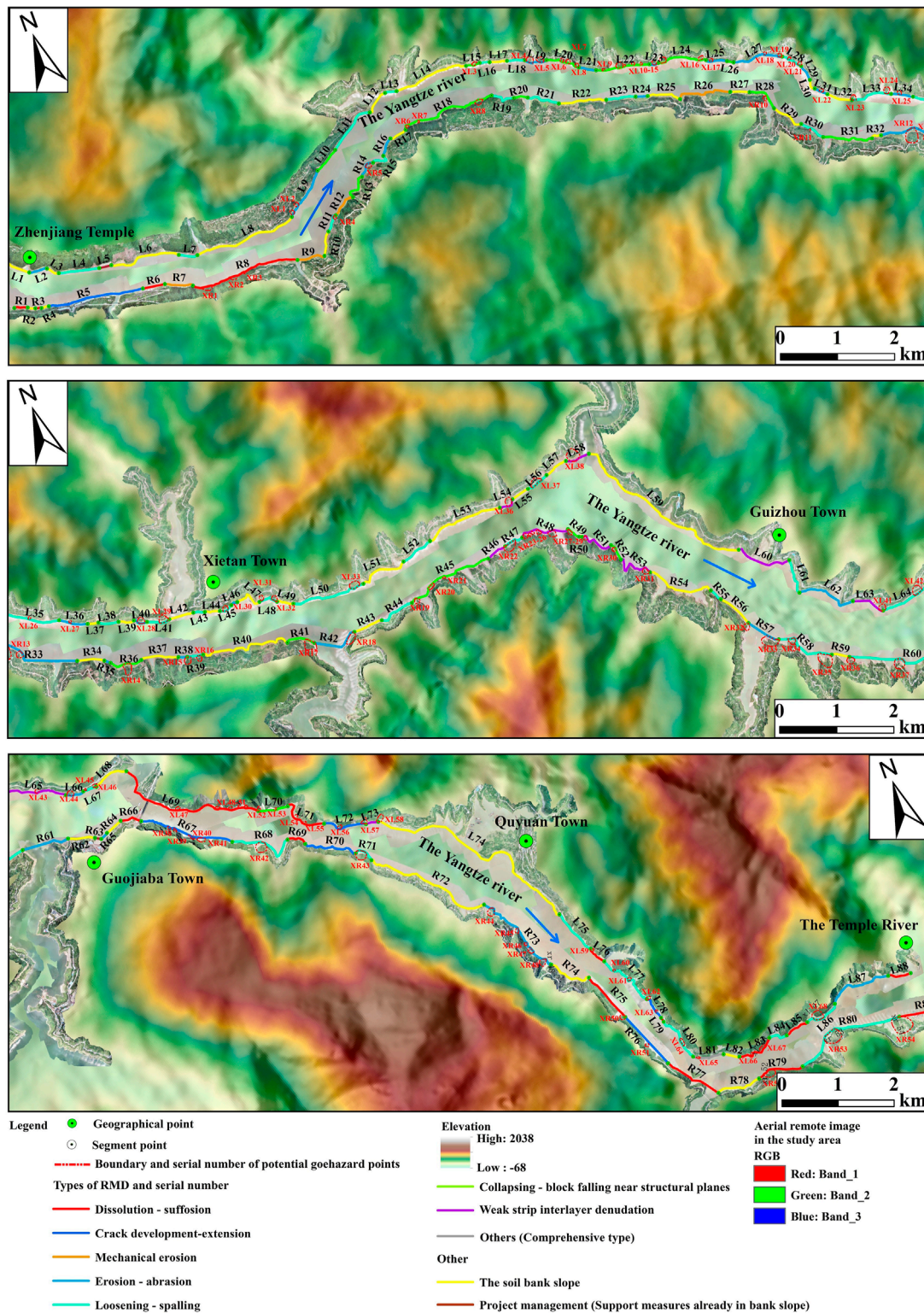


FIGURE 9 Boundaries of potential geohazards in the study area.

The area and volume of the landslide are about  $2.6 \times 10^4 \text{ m}^2$  and  $40 \times 10^4 \text{ m}^3$ , respectively. The neighbouring landforms are mainly the reverse bank slopes generally inclined towards the north direction,

the gradients of natural bank slopes vary between  $15^\circ$  and  $25^\circ$ , and the attitude of stratum is  $50^\circ \angle 35^\circ$ . The Yangjiaping landslide and its surrounding gentle slopes are mostly covered by the landslide



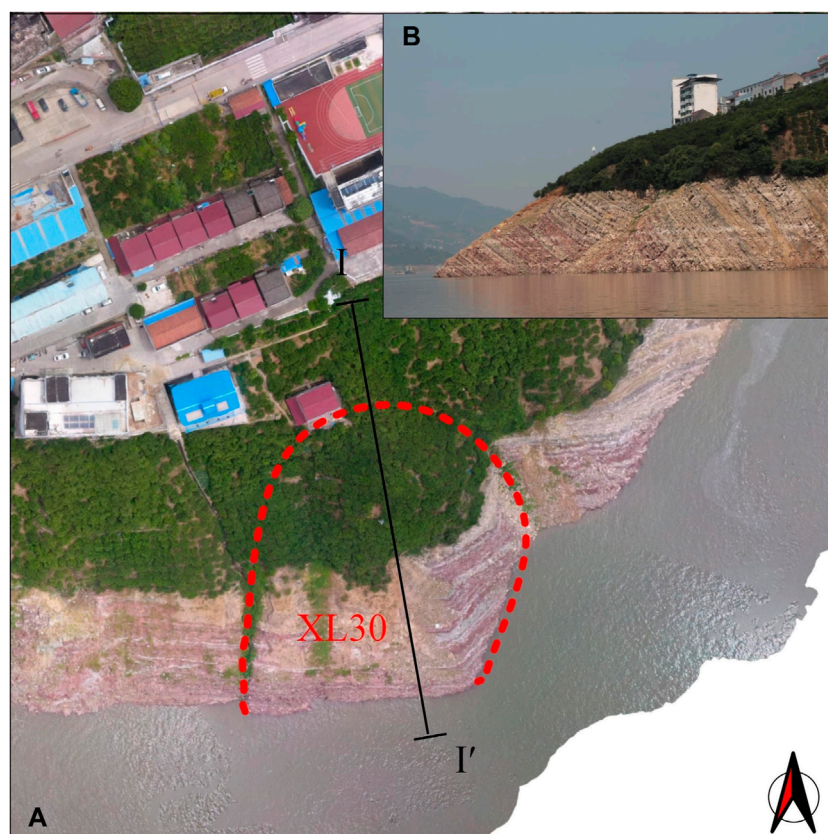


FIGURE 10  
The field verified Yangjiaping landslide: (A) aerial and (B) local range images.

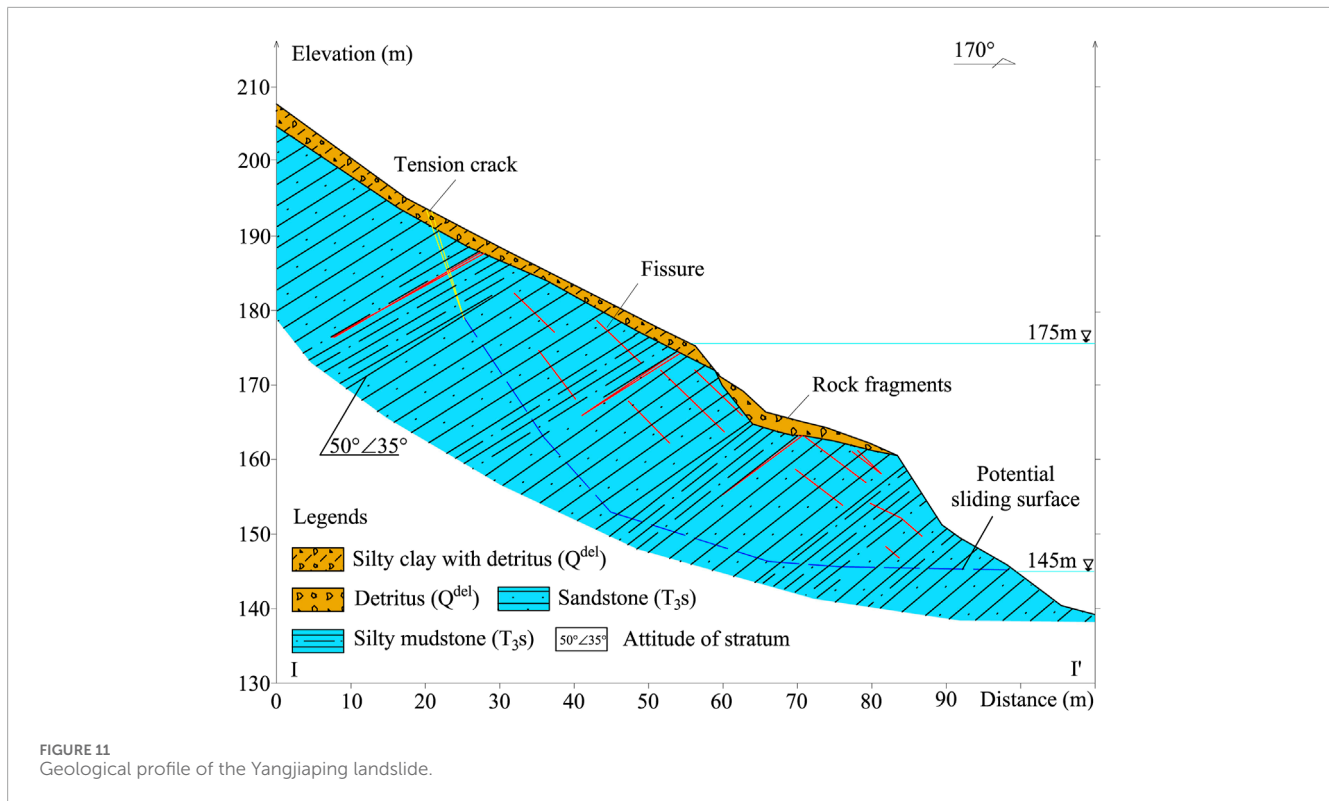
accumulation layer ( $Q^{del}$ ). The bedrock outcrops are common on the scarps, and the bedrock is mainly the clastic rock of the Upper Triassic Shazhenxi Formation ( $T_3s$ ) and the Lower Jurassic Xiangxi Formation ( $J_1x$ ). The rock masses of the Yangjiaping landslide are soft-hard interbedded, and mainly consist of hard sandstone and soft silty mudstone, as depicted in the Figure 11.

After the impoundment of the Three Gorge Reservoir, the HFB of the Yangjiaping landslide has been undergoing the long-term effect of water level change. Under the combined action of the water level fluctuation and wetting-drying cycles, the porosity or pores of soaked rocks increase and the dissolution of hydrophilic mineral components enhances, which results in the softening and disintegration of rocks. Then, the surficial fragmental rocks and the filling materials of discontinuities are washed away by the scour and erosion of flowing water. The interlayered soft silty mudstone are no longer able to support the overlying rock masses, and the overlying stratified hard sandstone begin to bend downwards under the unloading and gravity. The stress concentration near the slope surface results in the formation of tension fracture and the intensive extension of unloading fissures. Accompanying with the fracture and fragment of layered rock masses, the surficial rock masses lose the original structural integrity and collapse to form a zone of loose rock fragments with a certain depth. Currently, due to repetition of the previous process, a through step-shaped potential sliding surface has formed along the unloading fissures, and the tension crack at

the rear edge of the Yangjiaping landslide is filled with the rock fragments (Figure 11). It should also be noted that the local failure mode of the Yangjiaping landslide could be the planar rupture on the polygonal sliding plane, which can be formed by the tension cracks and unloading fissures.

## 4 Discussions

In order to clearly clarify the gaps between the existing remote sensing methods and the proposed photographic method in this study for recognition of reservoir geohazards, the interferometric synthetic aperture radar, as one of the typical remote sensing techniques, was selected for the comparative analysis with the presented photographic approach. The detailed comparative chart is depicted in the Figure 12. On the whole, these two methods both need to establish the high-precision three-dimensional terrain models of the study areas by integrating the DEM and the collected image data, and adopt the deformation or displacement indices of ground surface to identify potential reservoir geohazards. The main difference between these two methods is that the presented photographic method needs to zone the investigated area according to the types of RMD, and further to identify the potential RMD-induced reservoir geohazards according to the generalized evolution modes of typical cases. Moreover, the photographic approach developed in this study is objective-based,



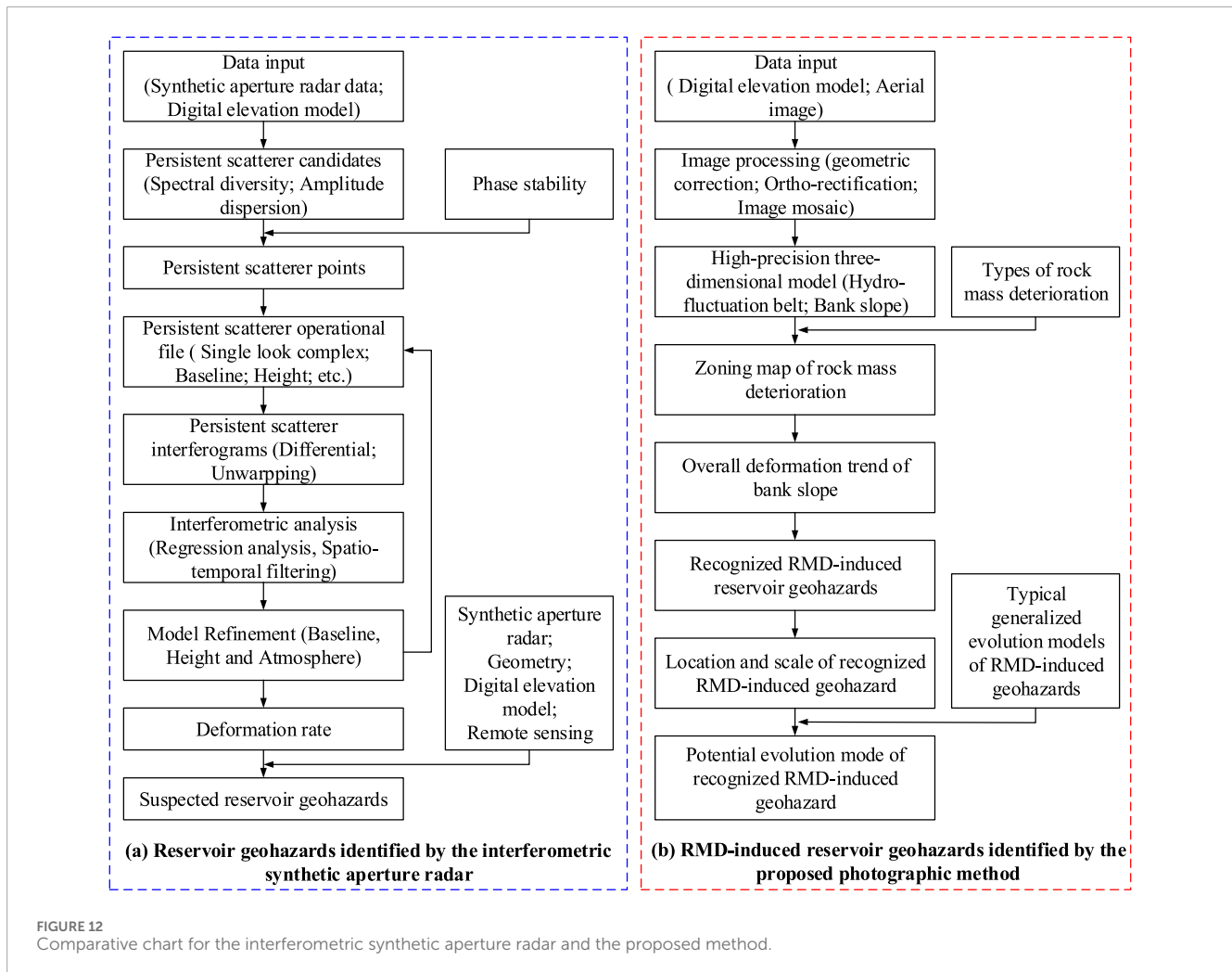
its usage is limited to the refined identification of RMD-induced reservoir geohazards.

Essentially, the RMD of HFBs in reservoir bank slopes is a long-term water-rock interaction process, which results in the continuous degradation of rock mass quality, namely, the loss of structural integrity and the decline of strength indices. Though the mechanisms of rock mass degradation under the periodic water-level fluctuation, such as one of the hydraulic, mechanical, thermal, and chemical effect, or the coupling of several aforementioned effects (Liu et al., 2008; Liu et al., 2009; Liu et al., 2018; Deng et al., 2012a; Deng et al., 2012b; Sun and Zhang, 2019; Liu et al., 2018; Yao et al., 2020; Wang et al., 2021; Zhou et al., 2021; Gu et al., 2021), are complicated and somewhat controversial, the consequences could be described by the degree of RMD, e.g., the rock mass degradation variable (Huang et al., 2021) or the damage deterioration variable (Yin et al., 2020a), and ultimately the potential geohazards induced by RMD proposed in this study (Figure 5). Thus, the evolution of the RMD-induced geohazard could be regarded as a dynamic catastrophic process, which is not only relevant to the type of RMD, but also highly depends on the degree of RMD. Though the novel method in this paper had an excellent performance in recognition of the RMD-induced geohazards in reservoir bank slopes, the accurate identification is far from sufficient to control the risk effectively. Since the established discrimination system only considers the type of RMD, the current state and development trend of the identified potential geohazards relied on the qualitative description of the type of RMD are not very clear, not to mention the risk of the identified potential geohazards. Hence, it is necessary to simultaneously consider the type and degree of RMD on the basis of the proposed method in future. For instance, by defining an index to quantitatively describe the degree

of RMD, the critical threshold of this index suggesting the transition from stability to instability of rock masses can be useful to judge whether a bank slope with RMD is in the risk of failure. Further, the aforementioned index also can be used in the risk assessment of RMD-induced geohazards adopting the conventional risk based framework, which begins with analysis of hazard and consequence, continues with risk estimation, and ends by risk evaluation. As to the risk analysis phase, after the identification of the instability mechanism of RMD-induced geohazards according to the generalized evolution modes presented in this study, the spatial and temporal occurrence (in term of probability) of RMD-induced geohazards and their intensity can be quantified based on the kinetic analysis of potential unstable rock masses, which accounts for the effects of RMD on critical influencing factors (such as the structure, strength and deformation parameters of rock masses) via the quantitative relationships between the index of the degree of RMD and other critical parameters. Since the predisposing factors, such as the degree of RMD and RMD-related indices, change over time, the time-dependent susceptibility or risk of RMD-induced reservoir geohazards also can be determined. For the administration departments related with disaster mitigation and prevention, the above work will contribute to determining the order of priority when the risk control measures or treatments of some potential geohazards, such as multi-row stabilizing piles (Pei et al., 2022; Zhang et al., 2022; Zhang et al., 2023), are about to be implemented.

To guarantee the reliability of the proposed photographic approach in recognizing the potential RMD-induced geohazards, the sufficient precision of original images of reservoir bank slopes acquired by the UAV photography is crucial. Considering the complicated and volatile topography and landforms of alpine valley regions, preplans for the emergency situations such as miserable





weather and signal interference should be prepared in advance when performing the UAV photography. In addition, the trial flights are essential to determining the preferable flight line, flight altitude, flight sorties, the degrees of forward overlap and side overlap. Herein, the software pix4Dmapper can be used to check out the integrity and the light-shade difference of successive images, and whether the overlapping area of the adjacent flights is sufficient. After the fast processing of three-dimensional point cloud data obtained by the UAV photography, the reliability of the data can be confirmed through the quality report yielded by the previous software. Meanwhile, the three-dimensional point cloud data is imported into the software pix4d to generate the data sets, and then to obtain the stereo data of three-dimensional model established by the software smart3D. To satisfy the precision requirement of orthophoto, the method of distinct block processing is selected to correct aerial photograph in the software pix4d. However, due to the extremely high pixels of synthetic image, the ordinary equipment is unable to handle the great number of primitive data without the help of particular serves. Therefore, the primitive data in this study was divided into suitable groups to generate the orthophoto by group, in which the number of the blocks ranged from 10 to 20 owing to the different data sizes of the blocks. The above procedure for generations of orthophoto and oblique real

scene three-dimensional model is usually time-consuming when meticulous geological mappings of potential reservoir geohazards are required. Thus, in terms of practicability of the proposed photographic method, future research on the technology for improving the data processing efficiency or the strategy for balancing the efficiency and the precision remains to be carried out.

## 5 Conclusion

In this study, a photographic method for recognition of the RMD-induced potential geohazards in reservoir bank slopes was presented and verified. The following conclusions can be drawn:

- (1) Typical evolution modes of the RMD-induced potential geohazards in the HFBs were proposed based on field surveys. The evolution modes in carbonate HFBs include base-crushing, toe-emptying induced toppling and bedding sliding, while the evolution modes in clastic HFBs include soft-hard interbedded rock collapse, apparent-dip wedge sliding, bedding sliding and reverse toppling.
- (2) In terms of the carbonate HFBs, base-crushing mode mainly occurs in dangerous rock masses; toe-emptying induced





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