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Development of Quick Digital Field Recording and Mapping Method of Geological Objects for Hydraulic Engineering

Wenchao Zhao [1,2], Shuai Han [2,*], Yapeng Chen [1], Yusheng Gao [1] and Manjie Liu [1]

[1] China Water Resources Beifang Investigation, Design and Research Co., Ltd., Tianjin 300222, China; wenchao69@163.com (W.Z.); chen_yp@bidr.com.cn (Y.C.); gao_ys@bidr.com.cn (Y.G.); liu_mj@bidr.com.cn (M.L.)
[2] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300354, China
* Correspondence: hs2015205039@tju.edu.cn

Abstract: During the fieldwork of hydraulic engineering, practical engineers normally document geological information manually. Although there are some GIS-based digital tools for geology, they are not perfectly applicable to hydraulic engineering. As a result, the current work mode is ineffective, unmanageable, error-prone, and not conducive to subsequent analysis. To address this problem, we developed a digital tool which enables geological recording and quick modeling based on 3D real scenes in the field of hydropower projects. There are three modules in the surface tool: object recording, image interpretation, and field analysis. The object recording module is to mark geological points (e.g., drills and shafts), lines (e.g., faults, stratigraphic boundaries), and surfaces (e.g., slope and stocking yard) on a 3D scene and then store them in the database. The image interpretation is to interpret the 2D information in images to 3D models loaded in 3D software for further studies, such as GOCAD. The field analysis includes surface fitting, stability analysis of blocks, occurrences calculating, rock recognition, and 69/sketching. The tool is helpful for recording data, drawing geological boundaries, and building a preliminary model in the geological survey.

Keywords: field geology; digital geological recording; 3D real scene of terrain; 3D geology model; hydraulic engineering

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1. Introduction

The traditional work mode of geological investigation in hydraulic engineering suffers from laborious data collection, subjective field analysis methods, and ineffective data management. Although there are many digital tools (such as MineScape [1] and FieldMove [2]) for geological engineering, they are not specifically developed for hydraulic engineering, which mainly focuses on the stability of multi-scale rock mass. As a result, in many cases, hydraulic engineers would rather document geological information manually.

There has been a rapid development in digital measuring techniques, especially with geographic information system (GIS), global positioning system (GPS), and remote sensing (RS) techniques. With the increasing popularity of GPS, the technique has been widely used in geology. The intelligent electromagnetic compass (IEMC) has also been used in geology, transformed from military and aerospace applications. Tablets have also been developed with fast processing speeds. However, the techniques are not typically integrated, and there is no unified database. Thus, it is necessary to develop a system integrated with GIS, GPS, and RS embedded in a mobile device as this will help improve efficiency and reduce labor and time costs.

The storage, access, and visualization of geological information has been studied for a long time. The interaction and accessibility of geology data are crucial. It is also studied for spatial data visualization, analysis, and exploration by integrating GIS, virtual reality (VR) and the internet [3]. Cooperation among the geo-information sciences, computer science, and mathematics is increasingly popular. Pavlis et al. [4] established a data model that can be applied to any GIS system and summarized the basic rules to building the model. Le et al. [5] studied the management of different types of geological data in a database management system. The further development of GIS benefits significantly from good management of different data types, and optimized data structure and software architecture keep systems in good working condition.

Multidimensional geology information can be described by geometric algebra [6]. However, it is also useful to analyze 2D geological pictures and draw geological boundaries using traditional methods. In MapIT [7], boundaries can be drawn, and profiles can be added onto 2D geological images. Qiu et al. [8] developed the Corel Geological Drafting Kit (CGDK) with visual basic for applications (VBA) for geological mapping, including stereographic projections and rose diagrams. It is a powerful tool that uses 2D geological pictures for geological field surveys. However, in reality, geological information exists in three dimensions. The integration of original geological data and the reconstruction of their 3D model will help engineers make decisions and avoid risks.

The presentation of 3D geological information has been well studied. Zhong et al. [9] built a 3D model in a complex geological condition based on non-uniform rational B-spline (NURBS) technique and the triangulated irregular network (TIN) method. It was also applied for stability analysis of key surface blocks of rock slope [10] and identification of complex rock blocks in a tunnel [11]. Klingbeil et al. [12] presented a direct-georeferencing system combining hardware and software to obtain a high-precision position of images taken with an unmanned aerial vehicle (UAV), with which a more accurate 3D model can be established. The UAV and terrestrial laser scanning techniques can be integrated to build refined 3D models [13]. The 3D geological information was also loaded into a system. Ming et al. [14] developed a 3D geological multi-body modeling system called GSIS, in which complex faults and multi-body 3D models were constructed based on cross-sections. Forno et al. [15] developed a 3D geomorphological survey and mapping tool called GSTOP, in which real-time location, drawing boundaries, and geological profiles were realized in a 3D model. Velasco et al. [16] built a tool that allowed the user to analyze and define the possible existing correlation surfaces, units, and faults based on an interactive 3D analysis environment. Touch et al. [17] built 3D geological modeling with commercial software to study boring log data. However, Breunig and Zlatanova [18] pointed out that the current geo-databases do not provide sufficient 3D data modeling or analyzing techniques. As a result, more efforts are needed for the development of a3D geological system.

The rapid update of smartphones has led to the development of geological surveys using mobile devices. This provides new methods for engineers to conduct geological surveys in the field. The famous GIS tools, e.g., Google Maps and ArcGIS, have basic functions such as displaying maps and drawing polylines on maps and are helpful for field work to a certain extent. However, they are not specifically used for geological surveys and lack professional functions, such as recording geological information in a specified format, conducting spatial analysis of geological data, and transmitting data to a geological database. An android application named GeoTool [19] was developed to measure the directions, strike, and dip of bedding planes. An IOS application named Smart Compass-Clinometer [20] was also developed to analyze geological stability. Wolniewicz [21] developed a tablet application named SedMob for creating sedimentary logs. The accuracy of the compasses on different platforms (IOS and Android) is studied [22]. It is convenient to save and extract logging information and easy to perform data synchronization in the remote server. However, all these tools or systems are mainly focused on recording data and can only provide two-dimensional perspectives; thus, engineers cannot develop a stereoscopic understanding of terrains and surrounding environments. Additionally, they lack spatial analysis functions and cannot help engineers figure out geological conditions effectively. In addition, the data fields present in them are not aimed at hydraulic engineering, so they are not suitable for the geological survey of hydraulic engineering.

Many geological objects need to be recorded and analyzed, such as lake water quality [23], boreholes [24], groundwater and surface water [25], and earthquakes [26] (Wang et al. 2016). Different modeling, recording, and analyzing methods are adopted for different geological objects, which can be described better by combining multiple methods [27,28]. In this research, we developed an integrated tool for the quick recording and analysis of geological objects. A quick evaluation of the geological condition can be performed using multiple methods, including geological object recording, interpretation of the 2D images, and 3D analysis of the geological condition. Moreover, in the 3D model, the accumulation of and the information extracted from images can be loaded into 3D modeling software for further analysis, such as GOCAD [29]. The tool in this research has a practical value to geological surveys.

2. Methods

The methodology architecture includes three parts, as shown in Figure 1.

(1) The 3D real scene terrain is the basis of the geological recording and the 3D analysis. There are two ways to build a 3D real scene terrain model in the SuperMap platform. The first way is to use UAV photos to build the detailed 3D terrain. The other way is to use a digital elevation model (DEM) and scene images to build the large-scale terrain model. The two terrain models show geological information at different scales.
(2) The geological recording can then be carried out on the 3D terrain. The geological objects and the 3D information extracted from images can be recorded according to the real coordinates.
(3) Based on the recording, 3D analysis can be conducted, such as accumulation body estimation and block instability analysis. Multiple methods are integrated to be a hierarchical one to build the whole system.

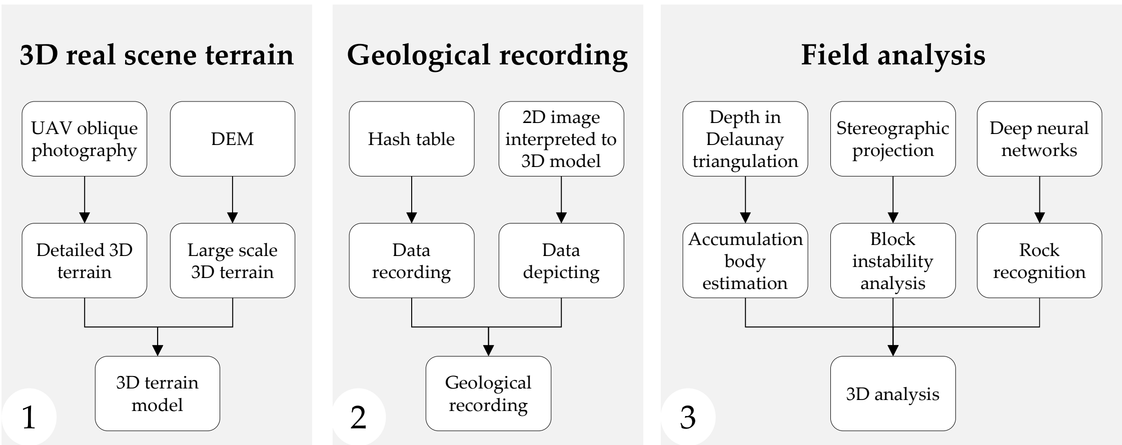


Figure 1. Methodology architecture.

2.1. UAV Oblique Photography and Modeling

In the detailed 3D terrain establishment, it is popular to build a 3D model using UAV oblique photography [30]. The oblique images are taken by a UAV camera, which can take photos at different angles, as shown in Figure 2. Therefore, the oblique images can show more information and match each other easily. Meanwhile, the oblique images have a large angle of view. They also have many different resolutions for the same geological object. As a result, it is convenient to conduct a 3D model with oblique images.

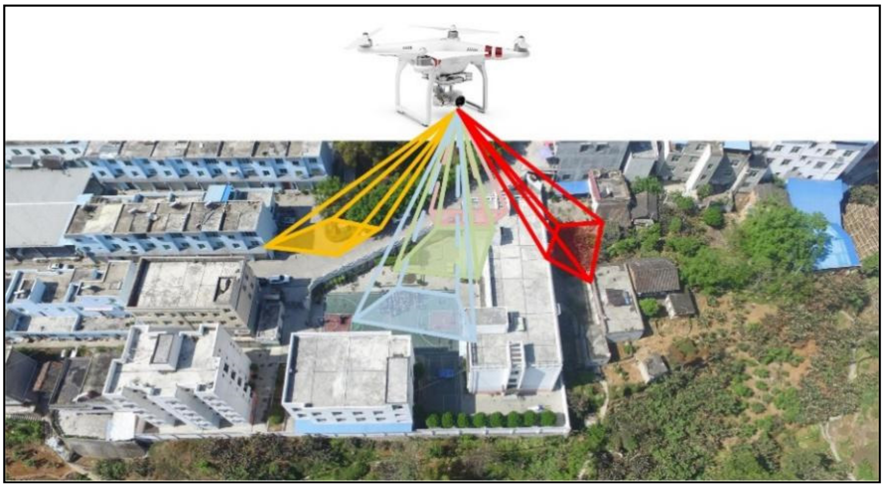


Figure 2. UAV oblique photography.

The point matching is applied to build the 3D terrain. The whole process is shown in Figure 3. First, a group of scene images is used to build the sparse point cloud. The same contents in different images are matched to show the whole terrain. The sparse point cloud can be reconstructed to be the dense point cloud using a depth map. Based on the dense point cloud, a mesh model can be established. The mesh model includes triangle and quadrangle mesh. Finally, the refined 3D real scene model can be built using the mesh model and the texture.

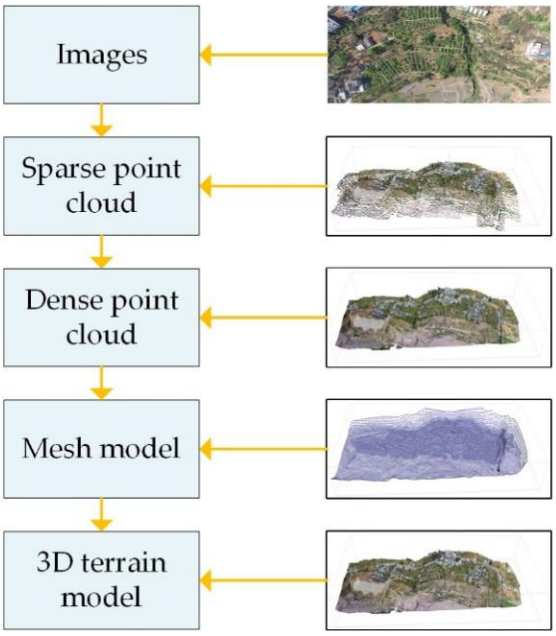


Figure 3. Three-dimensional terrain modeling process.

2.2. Data Recording

The data recording is the core part of the tool. In data recording, the data are saved in a structured storage mode. A hierarchical data model, designed based on a multi-dimension hash table, is used to manage the data recording. The layer class and order are taken as the index in the model. The name of the recording object is the key in a hash table. The complete information and attributes of the recording data are saved using the architecture, as shown in Figure 4. As a consequence, the data can be accessed and searched rapidly. The geological geometry is bound to the data recording and is saved with the data for the convenience of modeling and further analysis.

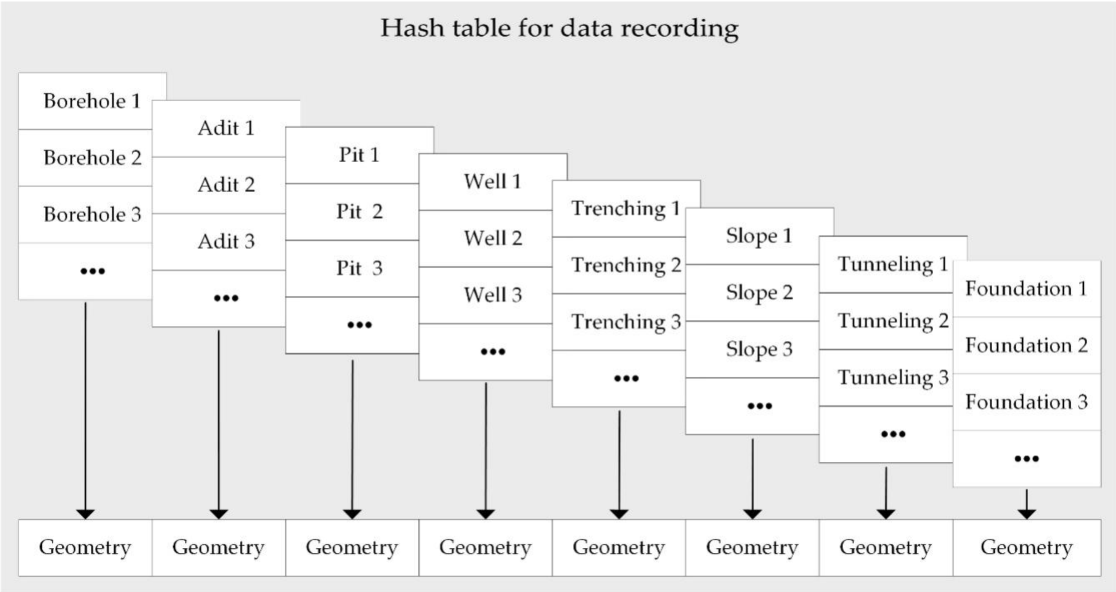


Figure 4. Data recording architecture.

2.3. Interpreting 3D Information from 2D Images

There are two steps to calculate the real coordinates of the geological objects in an image. First, perspective transformation is applied to change the scene of an image to a new viewing plane, which is parallel to the camera lens. The calculation is shown in Equation (1)

$$[x', y', w'] = [u, v, w]\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{1}$$

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn. u and v are the coordinates of the raw image; x and y are the calculated coordinates, $x = x'/w'$ and $y = y'/w'$; the transformation matrix $\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$ can be divided into four parts. $\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ denotes linear transformation, such as scaling, shearing, and rotation; $\begin{bmatrix} a_{31} & a_{32} \end{bmatrix}$ denotes translation transformation, and $\begin{bmatrix} a_{13} & a_{23} \end{bmatrix}^T$ is used to change the perspective. The coordinates can be calculated as in the following equations:

$$x = \frac{x'}{w'} = \frac{a_{11}u + a_{21}v + a_{31}}{a_{13} + a_{23} + a_{33}} \tag{2}$$

$$y = \frac{y'}{w'} = \frac{a_{12}u + a_{22}v + a_{32}}{a_{13} + a_{23} + a_{33}} \tag{3}$$

As a result, we can calculate the new coordinates of the geological objects by the transformation equation. Next, the known points in the image and real-world are taken as the control points to match the two following planes:

$$A_0x + B_0y + C_0z + D_0 = 0 \tag{4}$$

$$A_0'x + B_0'y + C_0' = 0 \tag{5}$$

Equation (4) is the plane in the real world and can be calculated by the known points. Equation (5) is the plane in the image. By matching the planes in different coordinate systems, we can calculate coordinate z values in the image and extract 3D geological information.

2.4. Depth in Delaunay Triangulation

The bottom surface of accumulation bodies can be estimated with the coordinates and the depth of each point using the Delaunay triangulation method. In Figure 5, the depth of control point M is known, and the depth of the other points can be calculated through interpolation.

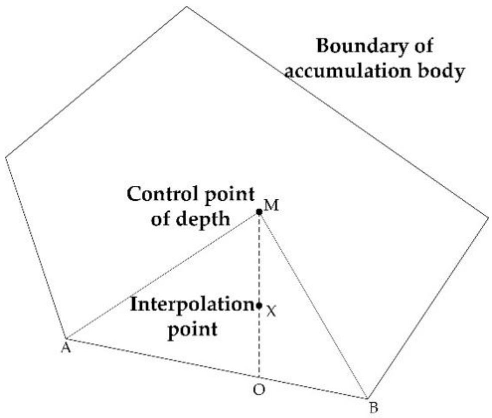


Figure 5. Depth calculation in Delaunay triangulation.

The coordinates of A, B, M, and X are known in the system. The equation of the straight line MX and AB can be obtained with Equations (6) and (7).

$$Ax_1 + By_1 + C = 0 \tag{6}$$

$$A'x_2 + B'y_2 + C' = 0 \tag{7}$$

$O(x_0, y_0)$ was obtained in Equation (8).

$$\begin{cases} Ax_0 + By_0 + C = 0 \\ A'x_0 + B'y_0 + C' = 0 \end{cases} \tag{8}$$

The lengths of D_m (MO) and D_1 (XO) were calculated, and the depth of the center point was the maximum. The lengths of other points were obtained by interpolation in Equation (9).

$$z_0 = z + \sqrt{1 - D_1/D_m} \times H_{\max} \tag{9}$$

where z_0 is the elevation of the points in the accumulation body, z is the elevation of M, D_1 is the length of XO, D_m is the length of MO, and $H_{\max}$ is the maximum of the depths, namely, the depth of the center point. The elevation of each point in the Delaunay triangulation was calculated, and smooth curves were joined to fit the bottom surface.

3. Development Tools and Requirements

The tool aims to work in the field of geological surveys. As a result, the portability of the tool is also considered. A tablet with a Microsoft Windows Operating System was selected. The specifications of the tablet are detailed in Table 1.

Table 1. Basic information of the tablet.

Hardware	Specifications
CPU	Intel® Core™ M-5Y10c Processor
Memory	4GB LPDDR3
Display Screen	1920*1080
GPS	A-GPS
Camera	Rear: 5 megapixels; front: 2 megapixels
Gyroscope	3-Axis gyroscope

The modules are integrated into the user interface designed based on WinForm, and the developed tools of the modules are Microsoft Visual Studio (Community Edition). All the platforms and components are presented in Table 2.

Table 2. Development platform and components.

Platform and Components	Details
Platform	Microsoft Windows
Framework	Net Framework
Underlying graphic platform	SuperMap iObject 10i
Framework of object-relational mapping	Entity Framework
Numerical analysis components	Math.Net
Deep learning components	TensorflowSharp
Computer vision components	EmguCV
Computational geometry components	MIConvexHull
Geographic information analysis components	CGAL

4. Module Integration on Tablet

In geological surveys, geological engineers need to record the geological objects (point, line, and surface) and then make further analyses based on the recorded information, such as estimating the accumulation body, evaluating block instabilities, and extracting information from images. Since the geological information is hard to analyze, three modules, object recording, image interpretation, and field analysis, were developed. Additionally, the 3D information extracted from the image and the estimation of the accumulation body can be loaded into 3D modeling software for further study. The architecture of the modules is shown in Figure 6.

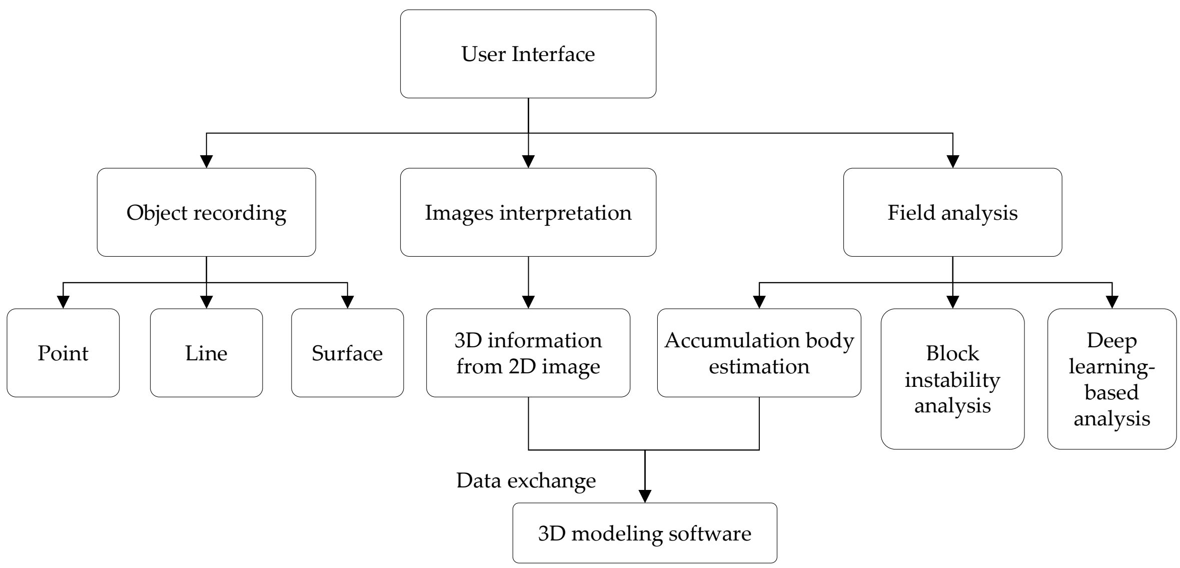
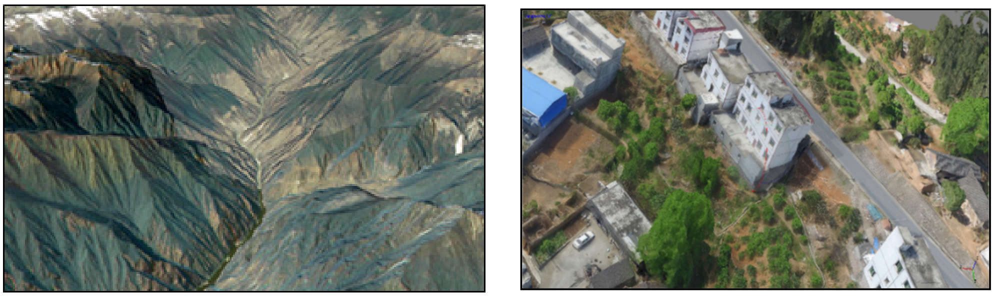


Figure 6. The architecture of modules.

The 3D real scene terrain includes the large scale and the detailed one, as shown in Figure 7. This is the basis of all the modules in the tool. According to the coordinates on the 3D real scene terrain, the objects can be recorded. In addition, a series of auxiliary functions were included, such as linear distance, horizontal distance, perpendicular distance, plane area, and surface measures.



(a) (b)

Figure 7. Three-dimensional real scene terrain: (**a**) large-scale 3D terrain; (**b**) detailed 3D terrain.

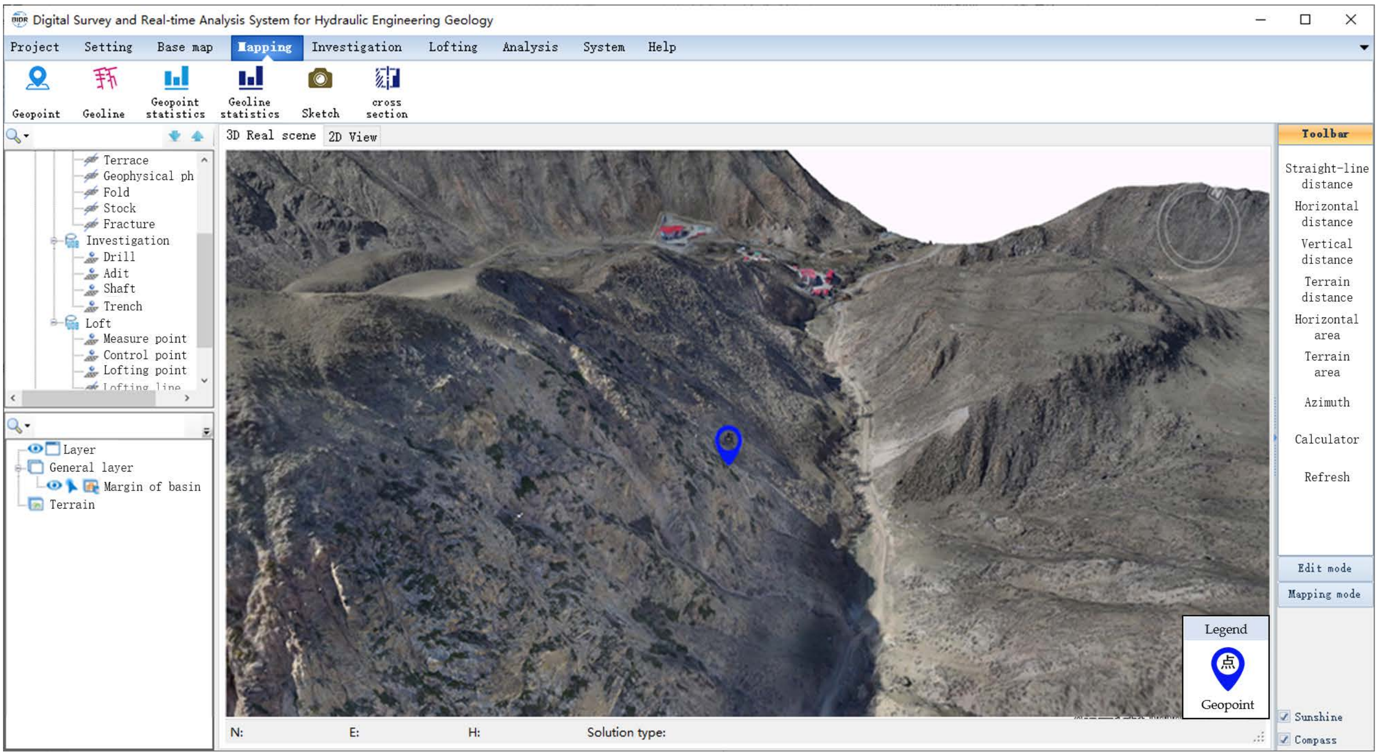
4.1. Object Recording

Objects include the point, line, and surface. The point is the basis of all the other objects. The module can obtain information about the device's location and orientation through the built-in GPS. Since the geological data are also located in 3D real scene terrain, the positions of geological data can be integrated into the 3D real scene when the coordinates are matched, as shown in Figure 8a. The point information, such as coordinates, depth, and type, is also saved, as shown in Figure 8b. There are many types of data that can be recorded in the system, such as borehole, adit, pit, well, trenching, slope, tunneling, and foundation. The line and surface can be drawn based on the recorded point data, as shown in Figure 9. The module can help geological engineers to gain a preliminary understanding of the spatial relationship of the geological objects.

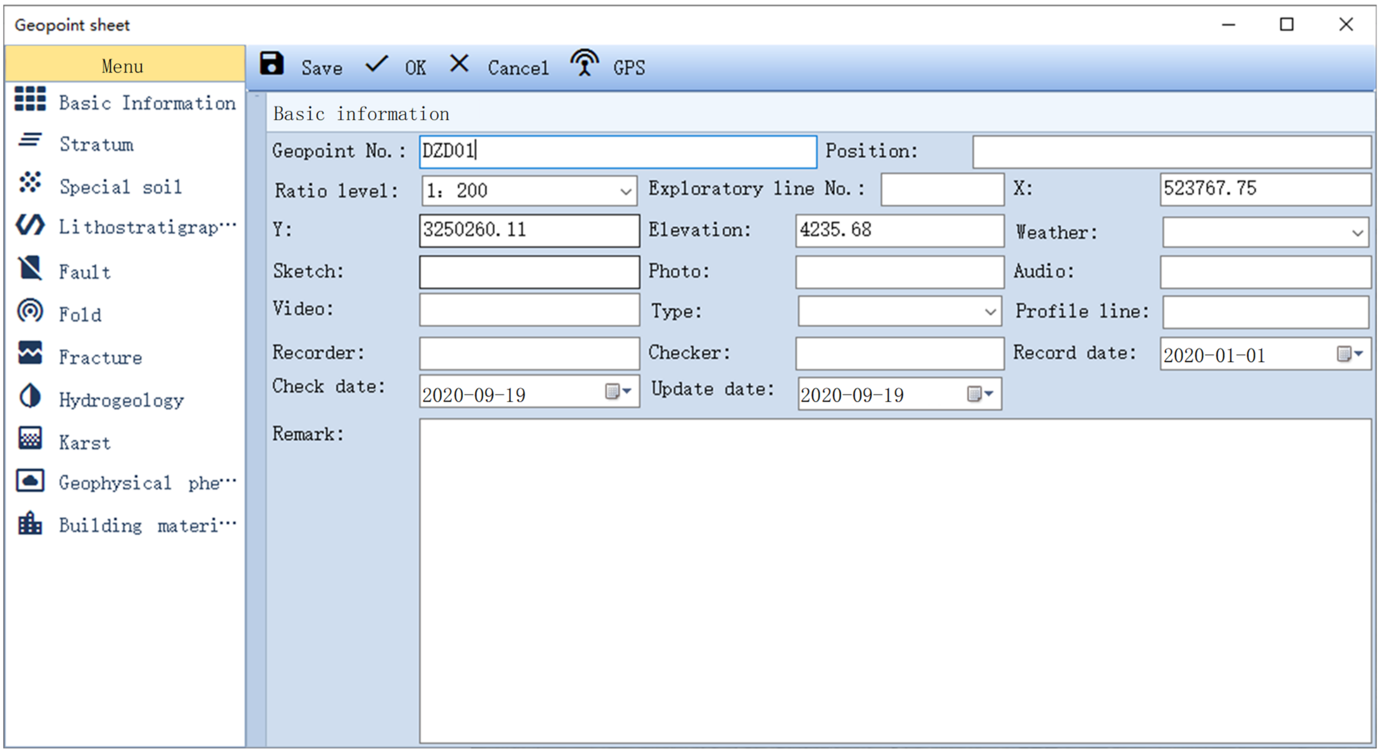
4.2. Image Interpretation

In geological surveys for hydraulic engineering, it is dangerous to record observations on a slope using traditional methods, especially since the slope with low rock mass is typically in geologically complex locations where landslides may occur. As a result, the geological information of artificially excavated or naturally occurring slopes is recorded with images. The information of structures is recorded as pixels, and it is necessary to save the image to store the complete geological information. However, this requires the database to save images. Moreover, it is difficult to establish models for analysis based on images. Therefore, an interpretation function was designed. According to the interpretation process shown in Figure 10, a geological image (e.g., slope image) is first loaded into the tool and then rectified with Equations (1)–(3). Next, the image's coordinate system is mapped to a three-dimensional space by fitting several control points with Equations (4) and (5) and the least square method. After that, engineers can plot polylines on the image, and the 3D information in the image can be extracted by matching the actual coordinates and the image coordinates.

An example of 2D image interpretation is shown in Figure 11. The depicted lines on the image can be recorded in different colors. The interpreted 3D geological information is saved in the database and can also be loaded into 3D modeling software for further analysis.



(**a**)



(**b**)

Figure 8. Geological data recording: (**a**) the recorded point on the map terrain; (**b**) the geological data recording card.

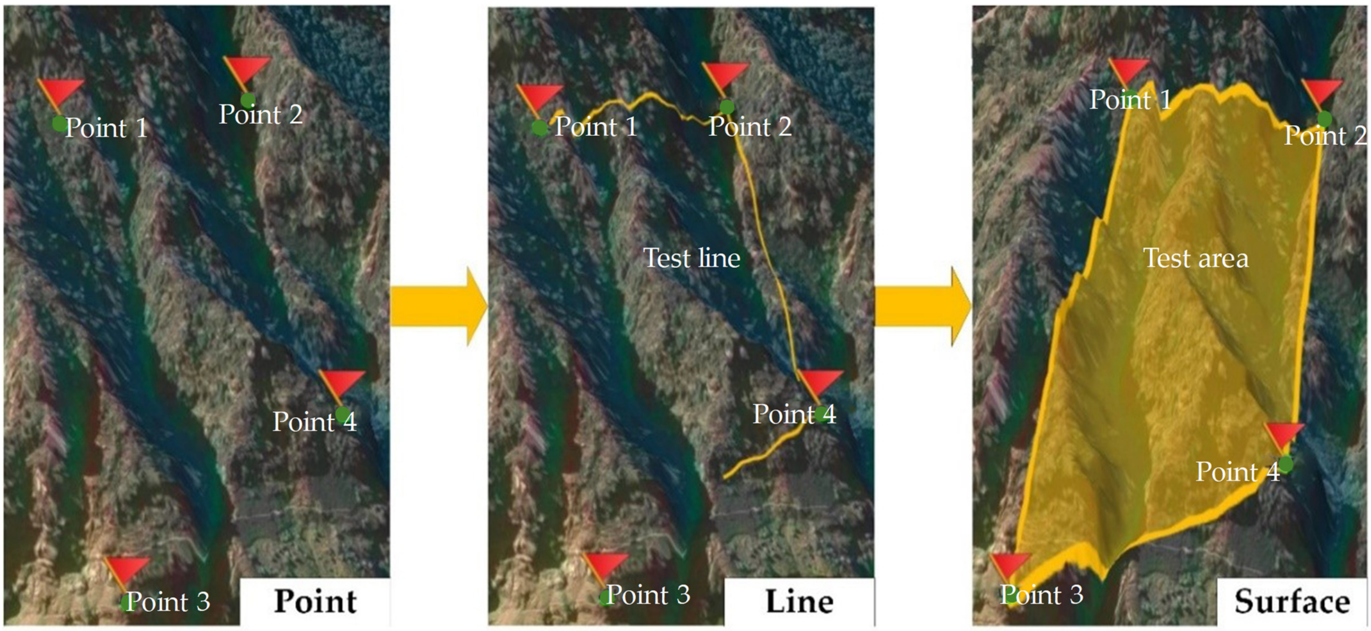


Figure 9. Object recording.

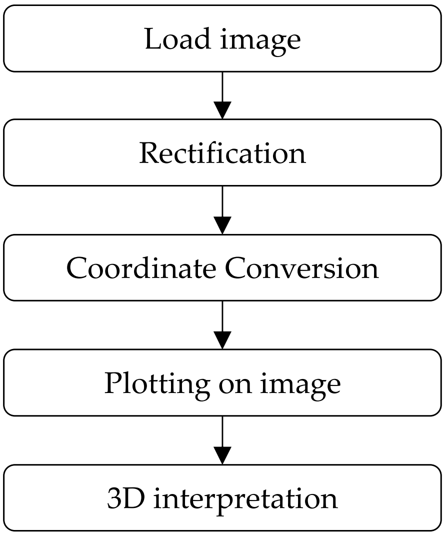


Figure 10. Process of image interpretation.

4.3. Field Analysis

4.3.1. Accumulation Body Estimation

The volume evaluation of accumulation bodies is important for the quality and cost control in hydraulic engineering construction, and the preliminary estimation of the bottom surface is crucial. However, in the design and survey stages in construction, the geological information is limited. Based on the method mentioned above, the bottom surface can be quickly estimated. The process of calculating the bottom surface of an accumulation body is shown in Figure 12. According to the set parameters, it takes the closed line as the boundary to build the Delaunay triangulation model as the bottom surface. The center depth is the input, and the result can be the output. The bottom surface can also be loaded into 3D modeling software for further analysis. The result is presented in Figure 12. The method is quick and effective in the preliminary geological survey of hydraulic engineering when the geological information is limited.

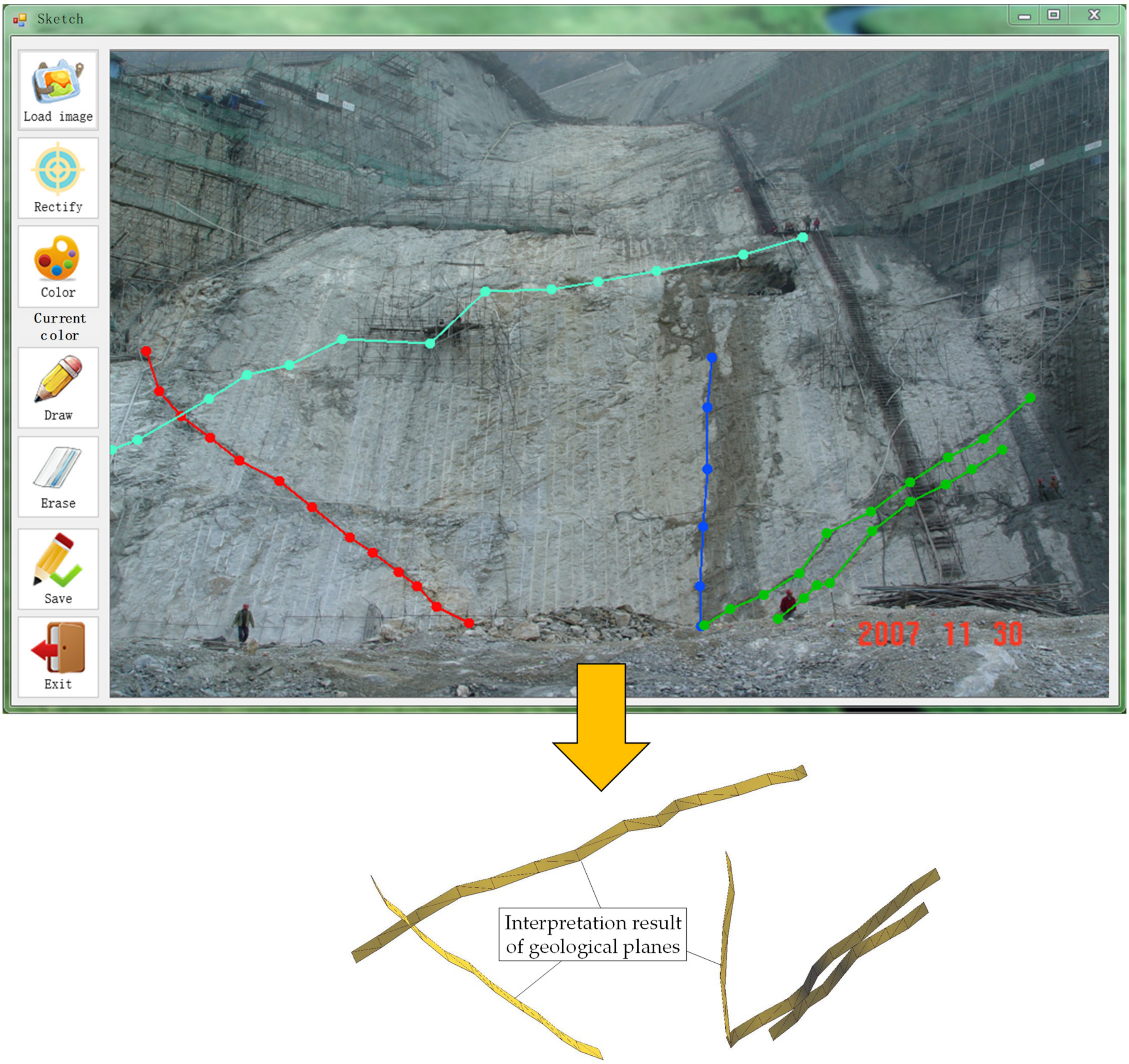


Figure 11. Process of interpreting 2D polylines into 3D models.

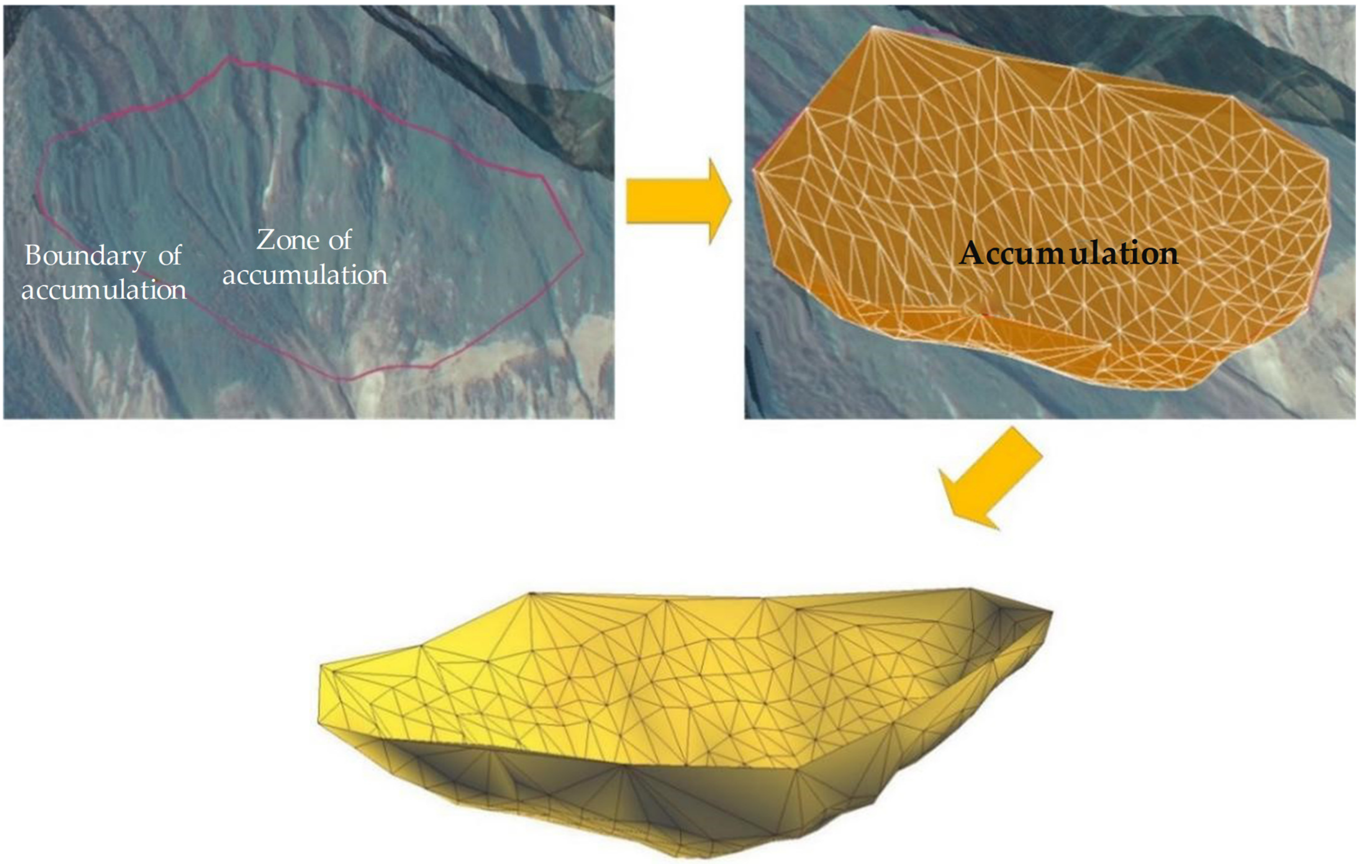


Figure 12. Bottom surface estimation of accumulation body.

4.3.2. Block Instability Analysis

Landslide and collapse are severe threats for hydraulic engineering; thus, block instability analysis for slopes is necessary. A block instability analysis module based on the polar stereographic projection method [31] was integrated into the system. The polar stereographic projection is a geometric approach that can determine the stability of slopes qualitatively. When the selected geological points were analyzed, the geological information of the slope was captured, as shown in the blue area in Figure 13. The intersections of free surfaces and structures were obtained according to the spatial relationship. A judgment regarding block stability was also made automatically in the tool, and the geological report of the selected area was outputted, which included detailed descriptions of the occurrences of fractures, intersection, block structure, block instability analysis, and direction of possible sliding in the report. Moreover, the report can be extracted as a text document. The process of block instability analysis is shown in Figure 13.

4.3.3. Deep Learning-Based Recognition for Rocks

In field surveys, determining the types of rock is the key to evaluating geological conditions. The traditional method mainly depends on the experience of engineers. In this software, the TensorFlow framework is integrated, and a deep learning model for rock recognition was established and trained using the method presented by Zhang et al. [32]. According to the methodology, the famous deep convolutional neural network, Inception-v3 model, presented by Google, was embedded, and the parameters pre-trained by the ImageNet dataset [33] were loaded. After that, the model was retrained with 3000 images that contained 20 kinds of rocks. The final validation accuracy is 0.955, and the cross-entropy is 0.434.

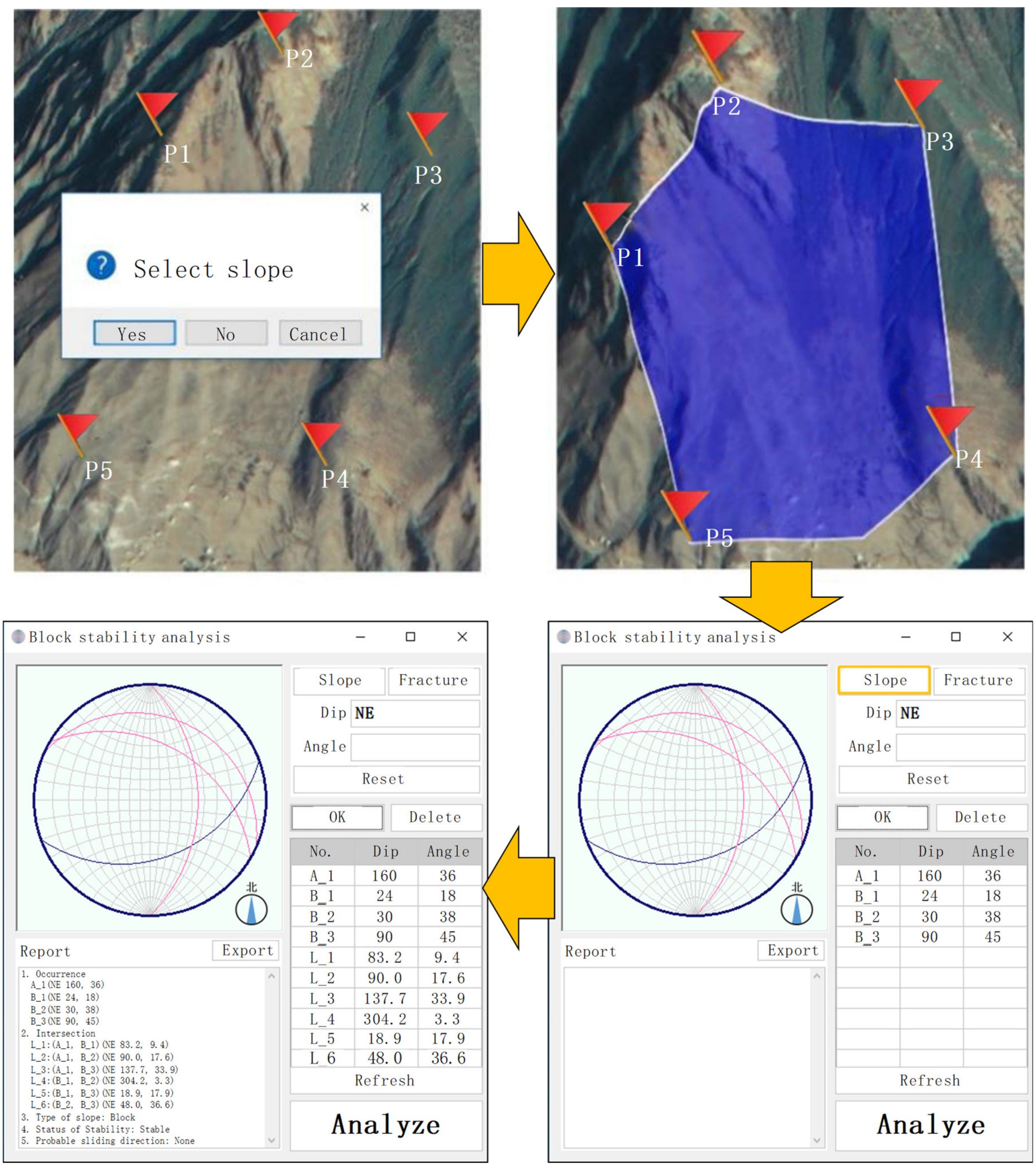


Figure 13. Block instability analysis.

5. Case Study

The tool was also applied in a geological survey of a hydropower project. It was a large engineering project in a complicated geological condition. The valley and slope were steep, and the angles of slopes were generally 30–90°. Mudslides, landslides, and land collapses are common in the area. Thus, the bad geological conditions have a negative influence on the project site selection. It is necessary to assess the potentially unstable area after impounding. Moreover, with the rise in the water level, there may be new geological hazards. We should record geological information and make a preliminary analysis, such as surface drawing and accumulation body estimation, in this area. Additionally, we should extract information from images. Figure 14 shows the traditional geological survey in hydraulic engineering.

Figure 14. Traditional fieldworks in hydraulic engineering.

The obtained information is loaded in a 3D modeling software to verify the proposed approach. As shown in Figure 15, the geological survey was mainly performed along the river. All kinds of geological information were recorded. Based on the recorded geological information, 3D analysis was performed in the tool, especially for accumulation bodies. The results are shown in Figure 16.

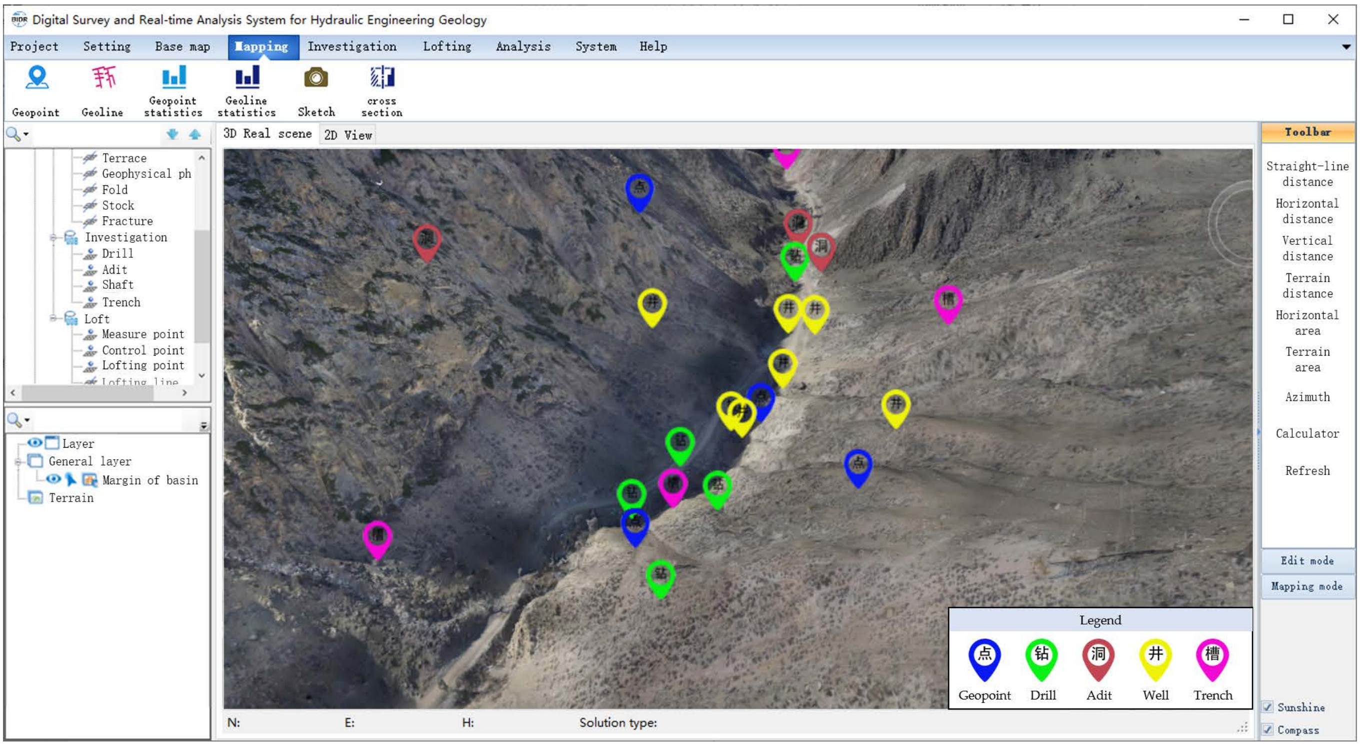


Figure 15. Results of a geological survey.

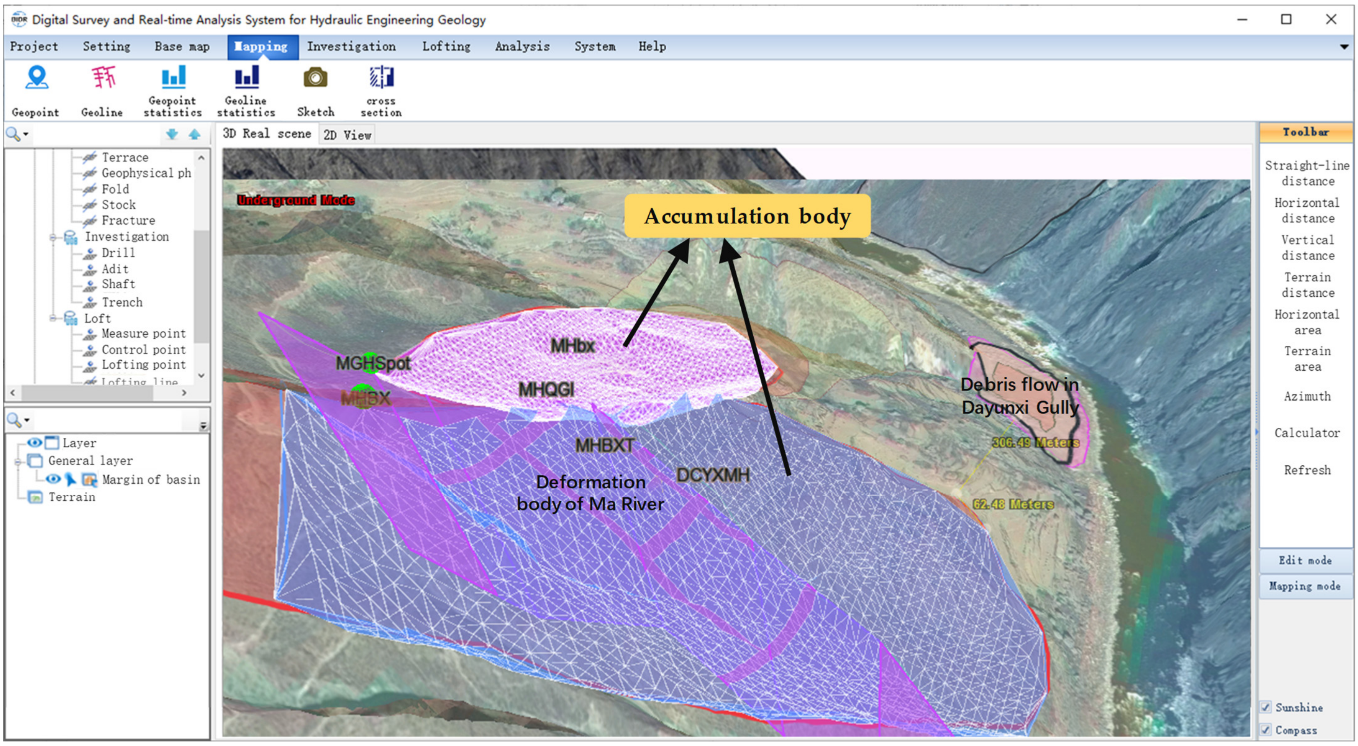
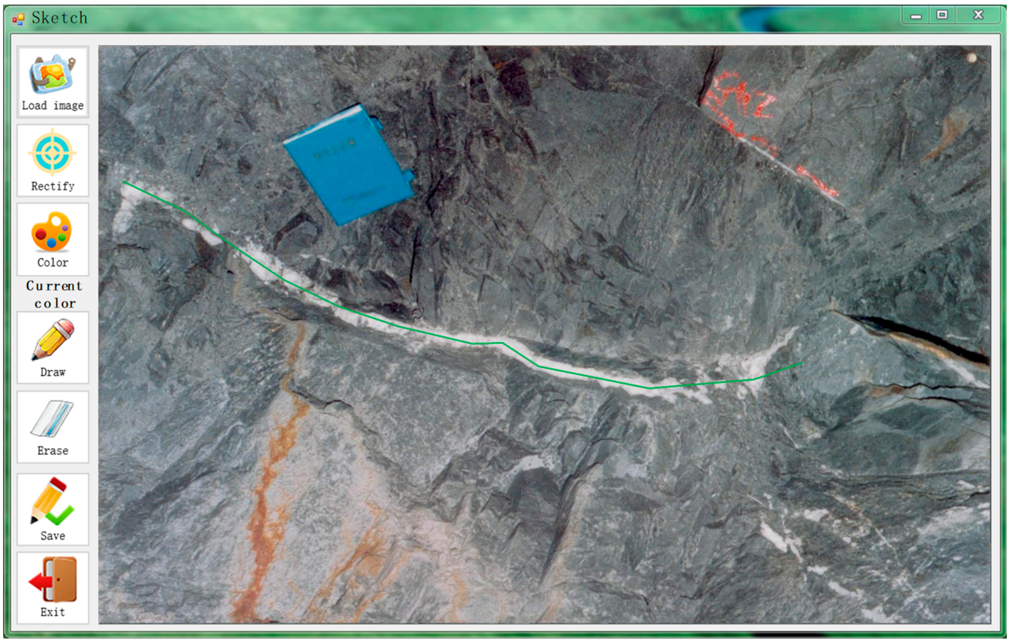


Figure 16. Results of accumulation body and occurrence estimation.

The geological information in 2D images was also converted into 3D information in the geological survey. Photo stitching was applied to show the effectiveness. The two strata, I and II, were recorded in the tool, as shown in Figure 17a,b. According to the actual coordinates, the two structures were loaded into 3D modeling software. Figure 17c shows the spatial relationship between the two structures. In Figure 17d, two photos were stitched to show the real positions of strata I and II, which proved the function's effectiveness.

(**a**)

Figure 17. *Cont.*



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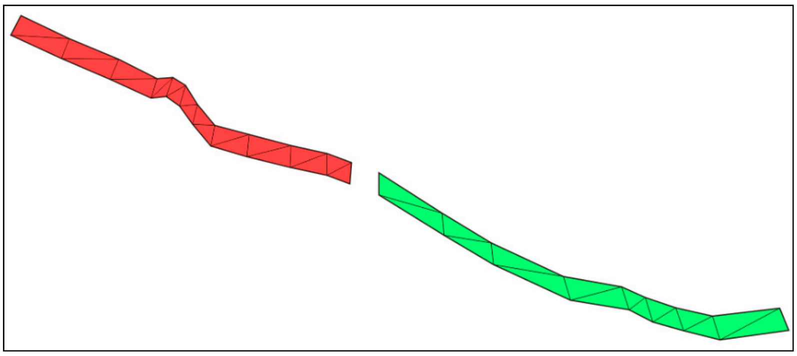
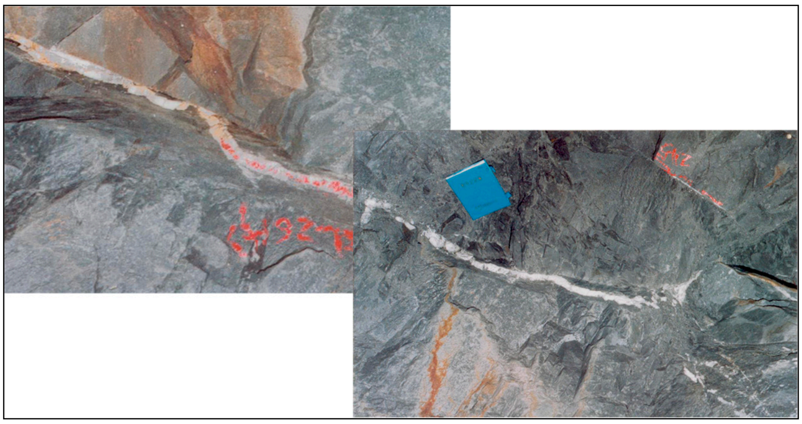


(**c**)



(**d**)

Figure 17. Two-dimensional image interpretation: labelling (**a**) strata I and (**b**) strata II; (**c**) 3D models of strata I and II loaded in a 3D modeling software; (**d**) two stitched images of strata I and II.

6. Conclusions

The geological survey of hydraulic engineering always suffers from ineffective data acquisition and backward field analysis and data management methods. In this research, three essential techniques for the digitization of the fieldwork of hydraulic engineering are proposed, namely, digital data recording, interpretations for 2D images, and computer-aided analysis for geological phenomena. The specific methods include (1) modelling for 3D real scenes, (2) structured storage for geological data, (3) interpreting from 2D images to 3D information, (4) evaluation of accumulation body, (5) block instability analysis, and (6) intelligent analysis for geological data.

To implement the above solution, we presented: (1) an oblique photography-based scheme for displaying the real field scene, (2) a hierarchical model for data storage, (3) a control point-based interpreting method for extracting 3D information from 2D pictures, and (4) a Delaunay triangulation-based method for the evaluation of accumulation bodies. Additionally, we chose the polar stereographic projection method for the instability analysis of slopes, and built a deep neural network for the intelligent recognition of rocks. As a result, all the above methods together with the techniques of GIS, GPS, and 3D modelling, were integrated into a digital tool.

The tool was also applied to a case study involving hydraulic engineering where information was recorded along the river that may negatively influence the dam. Based on the recorded geological information, a preliminary 3D geological analysis was performed to estimate the bottom surface of the accumulation bodies. In addition, it enables 2D images to be interpreted into 3D information that can be used for geological structural analysis. A comparison was made between the output results and the stitched photos, which proved that the method was influential in the case study.

In addition, it should be noted that the tool is for generalized and preliminary surveys, and aims at helping engineers acquire, manage, and analyze geological information in a highly efficient way during their field work. Therefore, the modules integrated in it are not based on complex calculations. For example, the presented estimation method for accumulation bodies needs engineers to set a center depth by experience. Technically speaking, this method is not rigorous enough. However, the exact depth of an accumulation body is challenging to determine in the field, but can only be calculated through extensive geological evidence and repeated trial-calculation in the lab. Therefore, the proposed method is to provide a reference for engineers for subsequent fieldwork. With the development of computer techniques and survey methods, the proposed solution and tool will be continuously improved to enhance the rigor of methods and the usability of the functions.

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References

1. Ey, M.; Sherval, M. Exploring the minescape: Engaging with the complexity of the extractive sector. *Area* **2016**, *48*, 176–182. [CrossRef]
2. Lundmark, A.M.; Augland, L.E.; Jørgensen, S.V. Digital fieldwork with Fieldmove-how do digital tools influence geoscience students' learning experience in the field? *J. Geogr. High. Educ.* **2020**, *44*, 427–440. [CrossRef]
3. Huang, B.; Jiang, B.; Lin, H. An integration of GIS, virtual reality and the Internet for visualization, analysis and exploration of spatial data. *Int. J. Geogr. Inf. Sci.* **2001**, *15*, 439–456. [CrossRef]
4. Pavlis, T.L.; Langford, R.; Hurtado, J.; Serpa, L. Computer-based data acquisition and visualization systems in field geology: Results from 12 years of experimentation and future potential. *Geosphere* **2010**, *6*, 275–294. [CrossRef]
5. Le, H.H.; Schaeben, H.; Jasper, H.; Görz, I. Database versioning and its implementation in geoscience information systems. *Comput. Geosci.* **2014**, *70*, 44–54. [CrossRef]
6. Yuan, L.W.; Yu, Z.Y.; Luo, W.; Lv, G.N. Geometric algebra for multidimension-unified geographical information system. *Adv. Appl. Clifford Algebr.* **2013**, *23*, 497–518. [CrossRef]
7. De Donatis, M.; Bruciatelli, L. MapIT: The GIS software for field mapping with tablet pc. *Comput. Geosci.* **2006**, *32*, 673–680. [CrossRef]
8. Qiu, J.; Song, W.; Jiang, C.; Wu, H.; Dong, R.M. CGDK: An extensible CorelDRAW VBA program for geological drafting. *Comput. Geosci.* **2013**, *51*, 34–48. [CrossRef]
9. Zhong, D.H.; Li, M.C.; Song, L.G.; Wang, G. Enhanced NURBS modeling and visualization for large 3D geoengineering applications: An example from the Jinping first-level hydropower engineering project, China. *Comput. Geosci.* **2006**, *32*, 1270–1282. [CrossRef]
10. Li, M.C.; Zhou, S.B.; Wang, G. 3D identification and stability analysis of key surface blocks of rock slope. *Trans. Tianjin Univ.* **2016**, *22*, 317–323. [CrossRef]
11. Li, M.C.; Zhang, Y.; Zhou, S.B.; Yan, F.G. Refined modeling and identification of complex rock blocks and block-groups based on an enhanced DFN model. *Tunn. Undergr. Space Technol.* **2017**, *62*, 23–34. [CrossRef]
12. Klingbeil, L.; Eling, C.; Heinz, E.; Wieland, M.; Kuhlmann, H. Direct Georeferencing for Portable Mapping Systems: In the Air and on the Ground. *J. Surv. Eng.* **2017**, *143*, 04017010. [CrossRef]
13. Jo, Y.H.; Hong, S. Three-Dimensional digital documentation of cultural heritage site based on the convergence of terrestrial laser scanning and unmanned aerial vehicle photogrammetry. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 53. [CrossRef]
14. Ming, J.; Pan, M.; Qu, H.G.; Ge, Z.H. GSIS: A 3D geological multi-body modeling system from netty cross-sections with topology. *Comput. Geosci.* **2010**, *36*, 756–767. [CrossRef]
15. Forno, G.M.; Lingua, A.M.; Russo, S.L.; Taddia, G.; Piras, M. GSTOP: A new tool for 3D geomorphological survey and mapping. *Eur. J. Remote Sens.* **2013**, *46*, 234–249. [CrossRef]
16. Velasco, V.; Gogu, R.; Vázquez-Suñè, E.; Garriga, A.; Ramos, E.; Riera, J.; Alcaraz, M. The use of GIS-based 3D geological tools to improve hydrogeological models of sedimentary media in an urban environment. *Environ. Earth Sci.* **2012**, *68*, 2145–2162. [CrossRef]
17. Touch, S.; Likitlersuang, S.; Pipatpongsa, T. 3D geological modelling and geotechnical characteristics of Phnom Penh subsoils in Cambodia. *Eng. Geol.* **2014**, *178*, 58–69. [CrossRef]
18. Breunig, M.; Zlatanova, S. 3D geo-database research: Retrospective and future directions. *Comput. Geosci.* **2011**, *37*, 791–803. [CrossRef]
19. Weng, Y.H.; Sun, F.S.; Grigsby, J.D. GeoTools: An android phone application in geology. *Comput. Geosci.* **2012**, *44*, 24–30. [CrossRef]
20. Lee, S.; Suh, J.; Park, H.D. Smart compass-clinometer: A smartphone application for easy and rapid geological site investigation. *Comput. Geosci.* **2013**, *61*, 32–42. [CrossRef]
21. Wolniewicz, P. SedMob: A mobile application for creating sedimentary logs in the field. *Comput. Geosci.* **2014**, *66*, 211–218. [CrossRef]
22. Whitmeyer, S.J.; Pyle, E.J.; Pavlis, T.L.; Swanger, W. Modern approaches to field data collection and mapping: Digital methods, crowdsourcing, and the future of statistical analyses. *J. Struct. Geol.* **2018**, in press. [CrossRef]
23. Tian, Y.; Huang, M. An integrated graphic modeling system for three-dimensional hydrodynamic and water quality simulation in lakes. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 18.
24. Lee, S.; Suh, J.; Park, H.D. Boreholear: A mobile tablet application for effective borehole database visualization using an augmented reality technology. *Comput. Geosci.* **2015**, *76*, 41–49. [CrossRef]
25. Tian, Y.; Zheng, Y.; Zheng, C. Development of a visualization tool for integrated surface water–groundwater modeling. *Comput. Geosci.* **2016**, *86*, 1–14. [CrossRef]
26. Wang, M.F.; Jiang, Q.A.; Liu, Q.J.; Huang, M. A new program on digitizing analog seismograms. *Comput. Geosci.* **2016**, *93*, 70–76. [CrossRef]
27. Bubniak, I.M.; Bubniak, A.M.; Gavrilenko, O.D. Digital field geology. In: Geoinformatics: Theoretical and Applied Aspects 2020. *Eur. Assoc. Geoscient. Eng.* **2020**, *1*, 1–4.
28. Senger, K.; Nordmo, I. Using digital field notebooks in geoscientific learning in polar environments. *J. Geosci. Educ.* **2021**, *69*, 166–177. [CrossRef]

29. Mallet, J.L. GOCAD: A computer aided design program for geological applications. In *Three-Dimensional Modeling with Geoscientific Information Systems*; Springer: Dordrecht, The Netherlands, 1992; pp. 123–141.
30. Nex, F.; Remondino, F. UAV for 3D mapping applications: A review. *Appl. Geomat.* **2014**, *6*, 1–15. [CrossRef]
31. Mauldon, M.; Goodman, R. Rotational kinematics and equilibrium of blocks in a rock mass. In: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. *Pergamon* **1990**, *27*, 291–301.
32. Zhang, Y.; Li, M.; Han, S. Automatic identification and classifcation in lithology based on deep learning in rock images. *Acta Petrol. Sin.* **2018**, *34*, 333–342.
33. Deng, J.; Dong, W.; Socher, R.; Li, L.; Li, K.; Li, F. Imagenet: A large-scale hierarchical image database. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, Miami, FL, USA, 20–25 June 2009; IEEE: Piscataway, NJ, USA, 2009; pp. 248–255.