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Original Research Article

DISCONTINUITY MAPPING IN NATURAL CAVES: A COMPARATIVE STUDY OF MANUAL DATA COLLECTION, STRUCTURE FROM MOTION, AND IPHONE 13 PRO MAX

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A b s t r a c t

The stability of shallow caves is significantly influenced by analysing rock discontinuities like faults, joints and stratification. Assessing these characteristics and identifying their orientations is essential for evaluating cave stability. Traditionally, this has been done manually with tools like a compass, but accessibility and time constraints limit these methods. Recently, remote sensing methods like Structure from Motion photogrammetry (SfM) and laser scanning have gained popularity for providing high-resolution models. This study compares manual measurements, SfM, and iPhone 13 Pro Max laser scanning for discontinuity mapping in Badajo Cave (Spain), evaluating each method's accuracy and efficiency. The results show a strong correlation between the methods, with an average measurement difference of around 5° for dip and dip direction, and the variation between methods was less than 7° in the worst case. The findings highlight the strengths and limitations of each method, with SfM providing high-resolution models but requiring considerable time for processing, and the iPhone 13 Pro Max offering quick results with some limitations in scanning range and accuracy.

Keywords: discontinuity mapping, natural caves, manual measurement, structure from Motion (SfM), laser scanning

1. INTRODUCTION

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The stability of rock structures like slopes and shallow caves is determined by various structural factors such as faults, joints and stratification [1,2], along with rock mass characteristics and weathering processes. An accurate identification of discontinuities is essential for precisely assessing their stability [1-4].

Generally, geotechnical practitioners and geologists determine deformation mechanisms and folding in rock masses through field investigations, documenting the orientation of discontinuities using tools like a geological compass with clinometer, scanline surveys, and measuring tapes [3-5]. In recent years, remote sensing technologies and digital geological surveys have provided enhanced insights into the characteristics of rock mass discontinuities [6-8].

Manual methods, using a compass remain common but have limitations due to reliance on visual assessment and hand-based measurement, both of these are heavily dependent on the operator's skill. and site accessibility [3-5]. Large caves, for instance, present significant challenges in accessing roof and wall sections for data collection, often confining geomechanical characterization to lower, accessible areas. This restricted access can lead to biased datasets, and to inaccurate evaluations of vulnerability to hazards and the dangers related to unstable rock structures [3-4,9].

The evolution of photogrammetry technologies, such as Structure from Motion (SfM), and innovations like the iPhone 13 Pro Max's 3D scanning capabilities, have gained widespread adoption in geomechanical analysis. These methods allow for the acquisition of high-resolution 3D models of rock surfaces, providing more precise and comprehensive data across larger areas in significantly shorter timeframes [6-8, 10-11].

The objective of this study is to present a comparative analysis of manual measurements using a compass, SfM, and the iPhone 13 Pro Max for discontinuity mapping [11], based on a case study of Badajo Cave, a shallow cave located in Segovia, Spain [9], highlighting the benefits and drawbacks of each method.

2. MATERIALS AND METHODS

2.1. Geomechanical Analysis and Data Collection with a Manual Compass

In fractured rock masses, the stability of shallow caves is influenced by the alignment and structural integrity of discontinuities. In such scenarios, tensile stresses and plastic deformation are usually absent; instead, the behaviour of the rock involves "rigid blocks" that move or shear relative to each other. This situation applies to the cave examined in this study, which is composed of a strong, fractured rock mass at a shallow depth (under 20 meters of cover).

In rock mechanics and geology, the alignment of discontinuities is typically described by dip direction and dip angle. The compass is the primary instrument used to determine orientation relative to magnetic north [3,5], necessitating physical access to the site (see Figure 1a). However, in the context of caves, this method presents certain limitations, because only the joints in the lower regions are accessible for measurement, as illustrated in Figure 1b.

Fig. 1. The challenges of manually gathering data in elevated areas of caves: (a) The requirement for a minimum of two people to gather data, (b) Challenges in reading the compass when measuring the roof and higher areas [3]

At our study site, we concentrated on collecting measurements from planes situated below 2 m. We utilized a Freiberger geological compass to measure the orientations of the discontinuities, which took approximately 30 minutes to complete, resulting in a total of 35 recorded measurements.

2.2. Photogrammetry SfM

Photogrammetry, a method used in remote sensing, obtains 3D spatial data from a series of photographs taken of a particular scene. This data collection process is grounded in the concepts of stereoscopic vision or the use of advanced 3D reconstruction techniques through automated matching algorithms [6-8]. Structure from Motion (SfM) offers an effective alternative, leveraging various concurrent images to calculate camera alignment settings without requiring prior adjustment [3-4, 10] (see Figure 2).

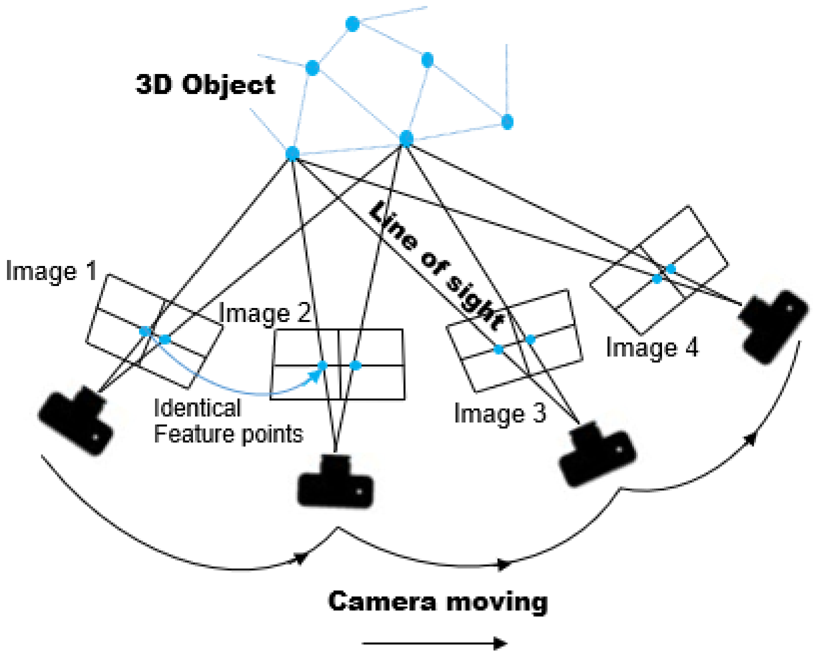

Fig. 2. The concept of SfM photogrammetry for 3D object modelling. Adapted and modified from [3]

The Structure from Motion (SfM) approach involves several stages: (i) identifying distinctive points in each 2D image; (ii) connecting these points across intersecting images; (iii) applying a bundle adjustment process to evaluate camera settings, aiding in the calculation of 3D coordinates and the preliminary creation of a sparse 3D point cloud; (iv) constructing a detailed 3D point cloud using Multi-View Stereo (MVS) techniques, which establish connections between points across multiple images; and (v) scaling and aligning the point cloud within a reference frame by at least three ground control points (GCPs). These GCPs, visible within the images, have known positions in the coordinate system [3-4, 10].

In accordance with the methodology outlined in [3], a total of 230 pictures were captured at the highest available resolution (1 Megapixel, 3:2 aspect; effective pixel count 3888 × 2592; RAW and JPEG file format) By means of a Nikon Coolpix 2800, an affordable camera with a fixed focal length of 10.4 mm and parameters adjusted for the typical lighting conditions within the cave. This approach aimed to rapidly construct a 3D point cloud using the Structure from Motion (SfM) technique. The generation of 3D point cloud was carried out with Agisoft Metashape v1.6 [12] based on the images. The processing level, which influences the quality of the results, was set to high precision to ensure effective visualization of the discontinuity sets. The modelling process required approximately 24 hours of computation to guarantee the necessary quality (see Figure 3).

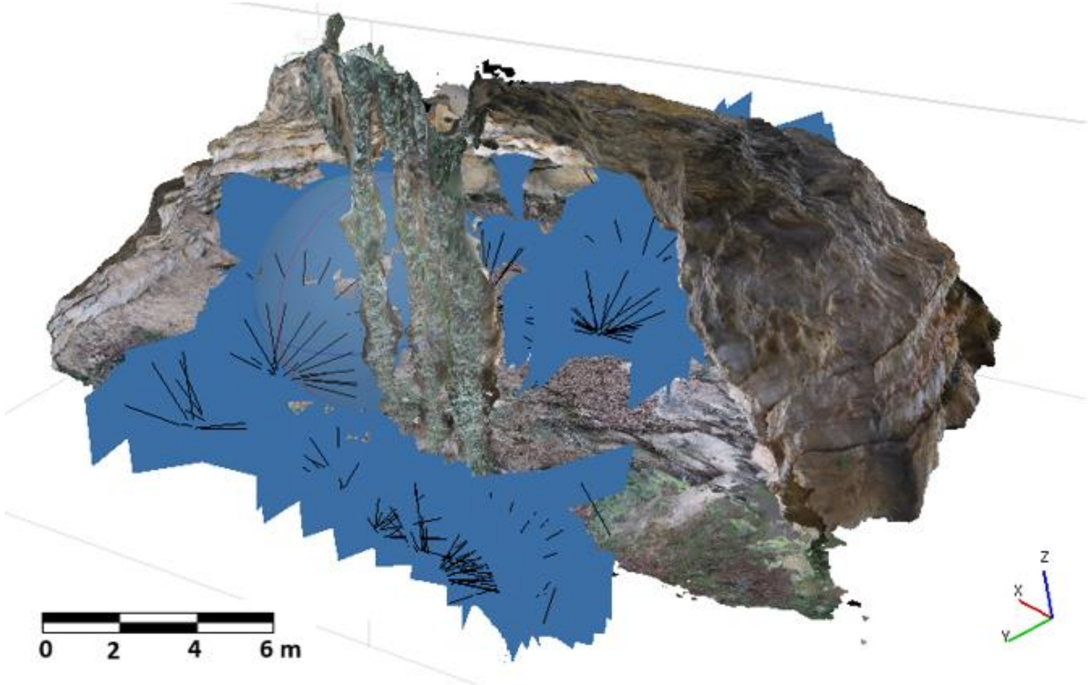

Fig. 3. 3D point cloud created using Agisoft Metashape. The blue markers indicate the locations where the photographs were captured

2.3. iPhone 13 Pro Max's 3D scanning

The iPhone 13 Pro Max, equipped with advanced LiDAR technology, offers the capability for generating 3D models through rapid scanning. LiDAR (Light Detection and Ranging) utilizes laser pulses to measure distances, providing precise spatial information about the environment. This technique enables the acquisition of high-resolution 3D data from the cave's interior in a fraction of the time required for traditional methods [11].

The process of scanning with the ScanUniverse application involves the following steps: (i) initiating the scan, where the LiDAR sensor emits laser pulses that reflect off surfaces; (ii) capturing the reflected signals to calculate distances and create a detailed point cloud representation of the cave; (iii) processing the point cloud data in real time to visualize the scanned environment; (iv) generating a textured 3D model that accurately reflects the geometry of the cave.

In Badajo Cave, the scanning process took approximately 10 minutes to complete, utilizing the iPhone 13 Pro Max with the ScanUniverse application, which was configured to capture large objects at a high-resolution setting under the typical lighting conditions found within the cave

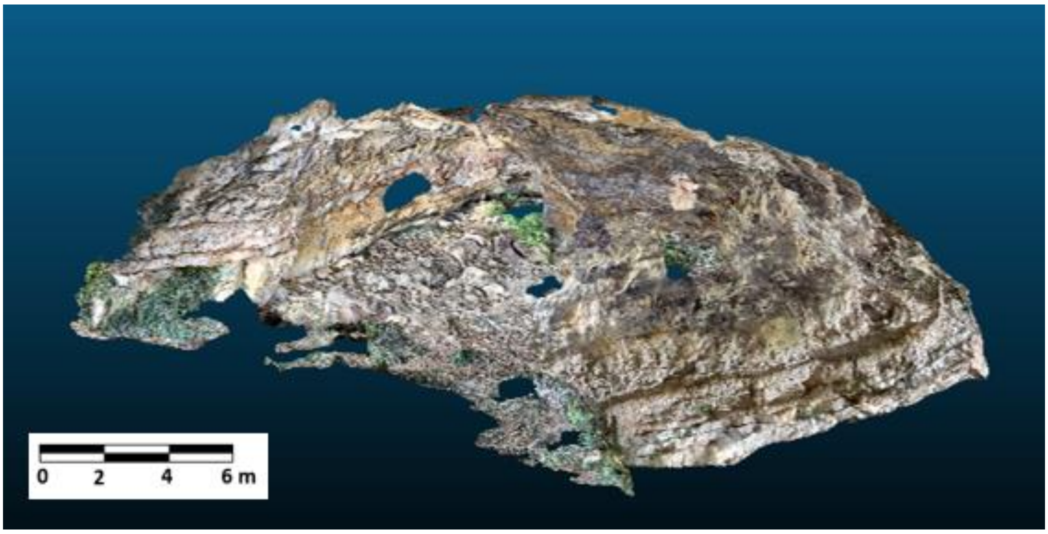

Fig. 4. Three-dimensional (3D) model obtained by iPhone 13 pro max. Screenshot from CloudCompare software v2.12.4

2.4. Portable Orientation Template

To properly orient and scale the 3D point cloud generated by Structure from Motion (SfM) and the iPhone 13 Pro Max, without the need for a topographic control equipment, a simple and economical instrument known as the "portable orientation device" has been utilized [3,10]. This device, which functions like a larger version of a standard compass, features five ground control points (GCPs) and three axes (x, y, z). The “y” axis can be oriented with true north via a compass, while a bubble level ensures the device is positioned horizontally. Once the GCP coordinates are determined, the device serves as a reference plane within the local (see Figure 6).

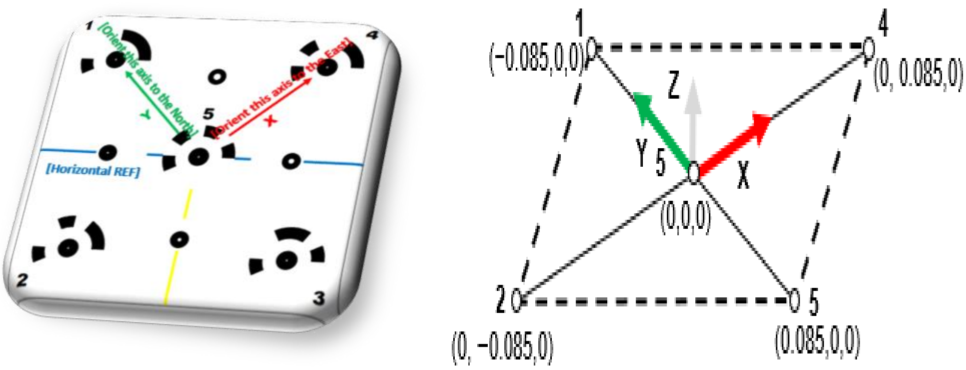

Fig. 5. The system used to set orientation, adapted and modified from [3]: (a) the template employed in the study; (b) GCPs coordinates in (m). (The green axis should align with the North, the red axis with the East, blue represents the horizontal reference, and yellow indicates the highest incline)

As part of our thorough evaluation of the 3D point cloud' quality, we performed an accuracy analysis. This involved comparing the actual coordinates of the ground control points (GCPs) with the coordinates derived from the models. Table 1 presents a summary of the discrepancies, and the calculated root mean square (RMS) error measurements obtained from the 3D point cloud models for each GCP. These RMS error values offer valuable information regarding the general precision and credibility of the models, which are deemed satisfactory [3,10].

Table 1. Total RMS of GCPs within the 3D point cloud models generated by SfM and iPhone

GCPs	Total RMS (mm)	
	SfM	iPhone
1	0.579607	0.888321
2	0.589086	0.430913
3	0.311125	0.805279
4	0.65416	0.92569
5	0.472141	0.877853

2.5. Review of the 3D Point Clouds and Identification of Discontinuities

Discontinuity sets from 3D point cloud models produced by Structure from Motion (SfM) and the iPhone 13 Pro Max were analyzed and identified through the t software Cloud Compare [13] and the next methodology. Initially, we performed a semi automated assessment utilizing the Facet ”Fracture Detection” plugin, which enables visualization of planar sets displayed in diffrent colors , with each colour corresponding to a distinct discontinuity family. Subsequently, the alignment of these joints was measured with compass tool by selecting specific points (see Figure 6). This approach facilitates the acquisition of orientation data in remote and challenging areas, as well as at higher elevations. In total, we collected 50 measurements from each model.

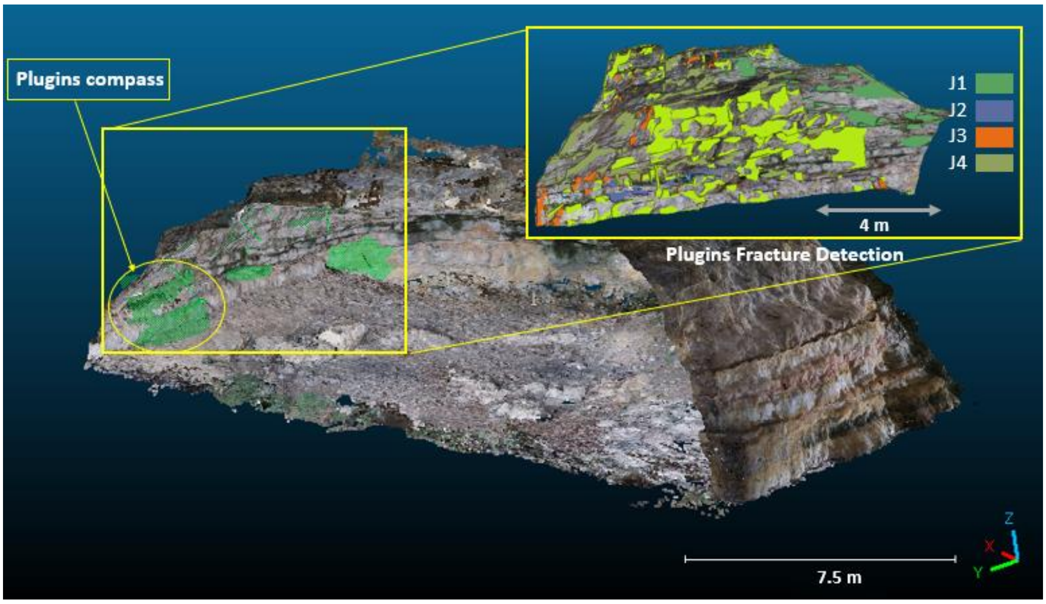

Fig. 6. Discontinuity characterization of Badajo cave using Cloud Compare software 2.12.4

3. RESULTS AND DISCUSSION

Discontinuity sets were determined using two approaches: (i) field measurements conducted using manual compass and (ii) results extracted from the 3D point clouds generated by SfM and the iPhone 13 Pro Max, utilizing Cloud Compare software. The results are presented in Figures 7.

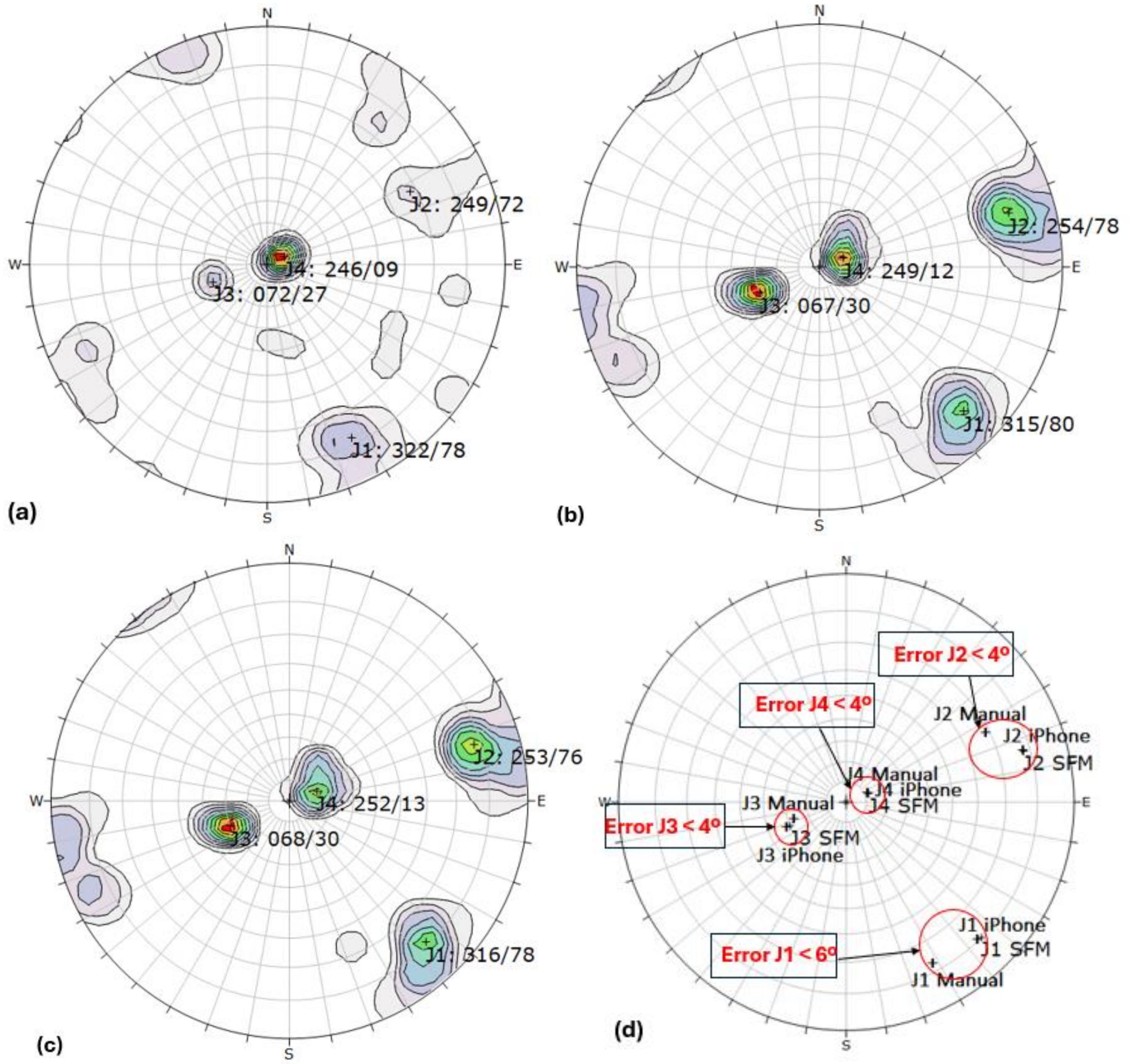

Fig. 7. Pole concentration stereogram for Badajo cave via the software DIPS: (a) field readings with a compass (n = 35 poles), (b) data obtained from a 3D point cloud generated by SfM (50 poles), (c) data extracted from a 3D point cloud generated by iPhone 13 Pro Max (50 poles), (d) contrasting manually measured planes with those obtained from 3D point clouds (SfM) and iPhone 13 Pro Max

Figure 7a displays 35 poles manually measured using a compass in the field, distinguishing four principal joint sets (J1, J2, J3, J4) along with their respective dip and dip direction. In contrast, Figure 7b shows 50 poles extracted from the 3D point cloud generated by SfM, where a higher density of data is evident for joints J1, J2 and J3 compared to Figure 7a. Similarly, Figure 7c presents 50 poles derived from the 3D point cloud generated by the iPhone 13 Pro Max, with results closely matching those of the SfM models. The slight differences observed are attributed to the manual selection of points in Cloud Compare. Figure 7d illustrates a comparison of the orientation data for the principal planes, revealing a high degree of similarity across methods, with only minor variations in pole scatter.

Table 2, 3 and 4 summarize the orientation values recorded by the different methods, offering a comparison of these values and identifying the discrepancies observed between them. This comparison helps to highlight variations in accuracy and consistency among the measurement techniques used in the study.

Table 2. Orientation values obtained by compass and SfM and the corresponding errors

	Manual Measurements Using Compass Dip Direction / Dip (°)	Data Acquired SfM Dip Direction / Dip (°)	Discrepancy Dip Direction / Dip (°)
J1	322/78	315/80	007/02
J2	249/72	254/78	005/06
J3	072/27	067/30	005/03
J4	246/09	249/12	003/03

Table 3. Orientation values obtained by compass and iPhone and the corresponding errors

	Manual Measurements Using Compass Dip Direction / Dip (°)	Data Acquired iPhone Dip Direction / Dip (°)	Discrepancy Dip Direction / Dip (°)
J1	322/78	316/78	006/00
J2	249/72	253/76	004/04
J3	072/27	068/30	004/03
J4	246/09	252/13	006/04

Table 4. Orientation values obtained by SfM and iPhone and the corresponding errors

	Data Acquired SfM Dip Direction / Dip (°)	Data Acquired iPhone Dip Direction / Dip (°)	Discrepancy Dip Direction / Dip (°)
J1	315/80	316/78	001/02
J2	254/78	253/76	001/02
J3	067/30	068/30	001/00
J4	249/12	252/13	003/01

4. CONCLUSIONS

The purpose of this research was to assess three approaches for acquiring joint set data: (i) traditional on-site data gathering with a compass, (ii) remote data collection using photogrammetry Structure from Motion (SfM) and (iii) iPhone 13 Pro Max scanning with the aid of a point cloud software. The study primarily aimed on analysing the variations and resemblances in measurements of dip and dip direction. Related to the application of the methodologies, manual compass data collection has limitations due to reliance on visual measurements and access restrictions, resulting in data bias. In contrast, 3D point cloud generated by SfM are high-resolution models, but they require considerable time for photo capture and processing (computation time). The iPhone 13 Pro Max generates 3D models quickly; however, it has a scanning range limited to 5 meters, which is challenging in large caves, and its accuracy is lower when scanning large areas.

Overall, the findings indicated a high level of consistency between the compass readings and the results extracted from the 3D point cloud models. The variation in measurements was less than 7° in the worst case, with an average of around 5°. Both Structure from Motion photogrammetry and the iPhone 13 Pro Max proved effective for obtaining structural data.

However, a limitation regarding lighting conditions should be noted. Since normal lighting conditions were used during data collection, underexposed or poorly lit areas could have potentially affected the SfM results, as the software requires well-lit and properly exposed images to generate accurate point clouds. This is an important consideration for future studies, where enhanced lighting or alternative data collection strategies could be employed to improve results, especially in challenging lighting environments.

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