

Application of Smartphone LiDAR Technology for Road Slope Monitoring

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Abstract. 3D modelling has become a dominant approach in scientific and engineering analyses, allowing for the collection of more precise data in significantly less time compared to conventional measurement methods. However, technologies that generate 3D data, such as terrestrial laser scanners (TLS), are often costly, which drives the need for more affordable alternatives without compromising accuracy. This paper presents a relatively new methodology for structural data acquisition using a smartphone as a low-cost tool equipped with LiDAR technology. Since the introduction of the iPhone 12 Pro, all subsequent iPhone Pro and iPad models have been equipped with integrated LiDAR sensors, making this technology widely accessible. The paper represents the third validation of this approach, expanding on the results obtained in two previous studies of similar scope. The study area is located along the regional road connecting Shtip and Negotino through Mount Serta, where steep slopes have been excavated in flysch - sandstones, conglomerates, and claystones. These lithologies are highly susceptible to weathering, and rockslides are common along this section of the road. To document the structural characteristics of the slopes, LiDAR scanning was conducted using an iPhone 15 Pro. The resulting 3D point cloud was georeferenced by combining reference dip and dip direction measurements taken with a geological compass. Georeferencing and subsequent analysis of the 3D point cloud were performed in CloudCompare software. Structural elements such as bedding planes and fracture sets were extracted, and their orientations were compared to conventional compass-based measurements. The results demonstrate that dip and dip direction values derived from the smartphone-based LiDAR scans show highly promising agreement with traditional field measurements, highlighting the potential of this low-cost method for reliable structural characterization and slope stability assessments.

Key words. iPhone, Geological compass, road, slope, 3D point cloud.

1. INTRODUCTION

The rapid development of technology across all spheres of daily life has led to the creation of advanced tools for data collection, analysis, and processing. In construction, geotechnics, and geology, innovative technologies are increasingly applied to improve both efficiency and accuracy. Complex systems integrating laser technologies, global positioning systems, and powerful computer hardware, in combination with continuously evolving software solutions, enable the processing of large datasets through advanced algorithms.

In structural geology, one of the fundamental tools remains the geological compass, traditionally used to measure the orientation of geological structures. However, with the emergence of modern terrestrial laser scanners (TLS) based on Light Detection and Ranging (LiDAR) technology, it has become possible to acquire such structural orientations with high precision. Despite their effectiveness, TLS systems are costly, prompting the search for more affordable alternatives capable of delivering comparable levels of accuracy.

The commercialization of LiDAR technology in smartphones marks a notable step in this direction. While LiDAR has long been applied in vehicles, drones, and other platforms, its integration into mobile devices offers new opportunities due to their compactness, portability, and widespread availability. In 2020, Apple Inc. introduced the first smartphone with a built-in LiDAR depth sensor, complemented by an enhanced augmented reality (AR) application programming interface (API). The primary function of the LiDAR scanner is to measure light distances and capture depth information, enabling the creation of 3D meshes at true scale and vertical orientation. Although less advanced than professional TLS devices, smartphone-based LiDAR, when paired with appropriate software, has proven capable of producing useful 3D models. Among several available applications that are used with the phone's hardware, the 3D Scanner App has demonstrated high accuracy and was therefore adopted in this study.

Cloudcompare is the software that was used for 3D data processing. It provides multiple functionalities, including measuring distances, dips, and orientations, as well as extracting key structural attributes. One of the tools of particular relevance is the virtual compass, which allows for the determination of dip and dip direction of geological structures directly from the generated point cloud.

In this study, an iPhone 15 Pro was used to determine the basic geological features of a selected slope, testing the feasibility of smartphone-based LiDAR as a low-budget alternative to traditional instruments. The concept of scanning various lithological units with a device carried in one's pocket has the potential to transform the way structural geologists acquire field data.

Accordingly, this paper compares the measurements obtained with a traditional geological compass to those derived from smartphone-based LiDAR scanning. The case study was conducted on a slope composed of sandstones, measuring approximately 8×3 meters, located along the regional road on the southwestern slopes of Mount Serta in the central part of Macedonia. This slope represents a prominent relief feature suitable for comparative analysis using both methods.

This study builds on two earlier works [1], [2], which examined the compatibility of smartphone-based LiDAR for structural geology applications. While previous studies relied on georeferencing of point clouds with the assistance of precision GPS tools, the present study investigates an alternative approach. Here, georeferencing was performed in CloudCompare software using only a limited number of reference measurements of prominent planar structures on the slope. This approach represents the final stage of a broader research effort to evaluate the potential of the iPhone as a practical and innovative tool in structural geology, with a particular focus on road slope monitoring.

2. USED METHODS, HARDWARE, AND SOFTWARE

Traditional methods for structural measurements are based on direct physical access to the rock surface. Since the early 2000s, however, remote sensing techniques have been increasingly applied in various fields, particularly for the characterization of rocky slopes [3]. Within the scientific community, there has been growing interest in extracting discontinuity information from remote sensing-derived datasets.

The classical method for measuring dip and dip direction of planar surfaces relies on the use of a geological compass. This is performed by placing the compass directly on a flat rock surface, levelling it, and recording the orientation indicated by the magnetic needle and the angular scale. In this study, a Klar compass manufactured by the German company Freiburger Präzisionsmechanik was used (Fig. 1a).

Smartphone-based measurements were carried out using an iPhone 15 Pro, released in September 2023 by Apple Inc. (Fig. 1b). The device is equipped with a LiDAR instrument

mounted on the back, capable of scanning surfaces up to 6000 m² with high acquisition rates of up to 222,000 measurements per second [3].

Laser/LASER (Light Amplification by Stimulated Emission of Radiation) is a device that produces and emits a beam (or series of pulses) of highly coherent, directional, and phase-consistent electromagnetic radiation. Laser systems enable the acquisition of large volumes of 3D information from the terrain at extremely high recording rates [4]. The fundamental principles of TLS have been well established since the 1990s, with rapid growth in the scientific literature between 2005 and 2010. Petrie et al. [5] made a significant contribution to the understanding of these principles, while detailed methodological guidelines were provided by Hiremagalur et al. [6].

The LiDAR sensor used in iPhones, utilizes the time-of-flight (TOF) or pulse method for capturing depth information. This method involves emitting laser pulses and measuring the time it takes for the pulses to return after hitting objects in the environment. By calculating the round-trip time of the pulses, the LiDAR sensor can determine the distance to various points in the scene and create a depth map or point cloud representation of the surroundings (Fig.1c). Apple does not disclose the specific accuracy specifications of the LiDAR sensor in iPhones.

This technique generates a 3D point cloud, which can be analysed to detect discontinuity sets, determine their orientations, and extract associated parameters [7]. For data acquisition in this study, the commercial 3D Scanner App developed by Laan Labs was employed [8]. The app activates the iPhone's LiDAR sensor, located adjacent to the rear camera, to record surfaces. During scanning, the phone was held at approximately 0.3–3 meters from the target surface.

For subsequent data analysis, the open-source software CloudCompare was used [9]. CloudCompare is a versatile platform for processing 3D point clouds, capable of handling triangular meshes and calibrated images. It is available for Windows, Linux, and Mac OS X (both 32- and 64-bit architectures) and is developed in C++ with Qt. In this study, the Virtual Compass Tool within CloudCompare was employed to extract dip and dip direction values directly from the point cloud.



Fig. 1: a) geological compass b) iPhone 15 pro c) Principles of laser scanner data

3. RESULTS

The measurements obtained with the geological compass were systematically recorded in a field notebook. Simultaneously, photographs were taken at each location where the compass was applied (Fig 2b). This procedure ensured that, during subsequent processing in CloudCompare, the dip and dip direction could be measured with the Virtual Compass Tool at the exact positions corresponding to the field measurements (Fig 2c). In this way, control

measurements of the 3D point cloud (3DPC) were performed at identical points on the rock surface.

During data collection, certain rock surfaces were irregular and not perfectly planar. Consequently, measurements were taken only on those portions of the outcrop that provided sufficiently flat surfaces. To enhance reliability, three geological compass readings were performed at each measurement point. Correspondingly, three measurements with the Virtual Compass Tool were also conducted at each measurement point. The three measurements that are taken within a radius of approximately 20 cm often produced slightly different values for dip and dip direction. These variations were subsequently analysed in detail.

In total, 18 measurement points were established, with three measurements recorded at each point, resulting in 54 individual measurements (Fig. 2a). At locations where the rock surfaces were smoother, the results from the geological compass and the Virtual Compass Tool showed strong agreement, displaying very similar trends. In contrast, measurements conducted on more uneven surfaces exhibited greater deviations in the recorded dip and dip direction values for both instruments.

a)	Geological compass measurement			No	Virtual compass measurement		
	1	2	3		1	2	3
1	240/48	244/50	245/45	1	239/51	246/50	242/48
2	102/80	100/84	101/82	2	92/79	85/82	88/81
3	30/89	32/88	25/89	3	45/83	39/83	36/78
4	225/87	228/88	210/88	4	232/88	230/88	230/85
5	115/73	116/73	118/76	5	115/65	113/72	112/62
6	113/79	117/82	119/81	6	115/88	113/86	111/82
7	115/89	116/81	118/85	7	122/85	113/89	108/83
8	113/79	115/82	110/81	8	109/82	109/81	107/75
9	119/80	123/79	127/78	9	130/74	128/74	129/71
10	112/80	115/78	115/75	10	118/75	110/76	108/73
11	112/84	107/80	109/81	11	105/80	103/82	102/79
12	120/82	116/80	121/81	12	117/81	124/84	124/76
13	122/79	123/83	118/80	13	122/77	123/80	123/78
14	118/76	117/76	116/74	14	119/69	116/70	114/72
15	71/87	65/88	67/89	15	82/81	77/84	81/76
16	249/70	253/72	252/70	16	261/77	258/72	263/71
17	30/12	35/13	33/15	17	34/18	41/19	36/14
18	25/20	35/18	31/22	18	37/20	32/18	36/32

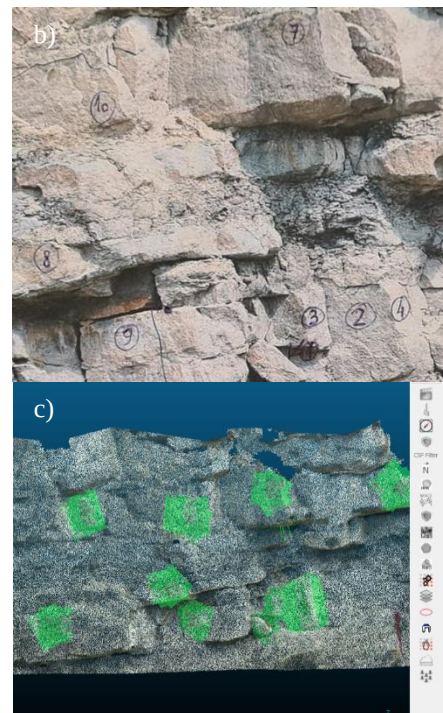


Fig. 2: dip and dip direction measurements b) marked measurements on a photo c) measurements using virtual compass tool.

3.1. Analysis of received deviations

When measuring with the geological compass, the maximum difference in azimuth of dip direction for three readings at a single measurement point was 18°, while the maximum difference in dip angle was 8°. For the virtual compass, the corresponding maximum differences were 14° and 14°, respectively. These results indicate that the trends of variation are similar for both approaches.

An analysis of the average differences within each set of three measurements at a single point provides additional insights into the compatibility between the two approaches. A frequency analysis of the differences obtained with the geological and the virtual compass was conducted to evaluate the distribution of deviations. The difference is expressed as the deviation of the virtual compass measurement relative to the geological compass measurement. The average

values of differences per point obtained with the virtual compass were subtracted from the corresponding average values obtained with the geological compass (Fig. 3).

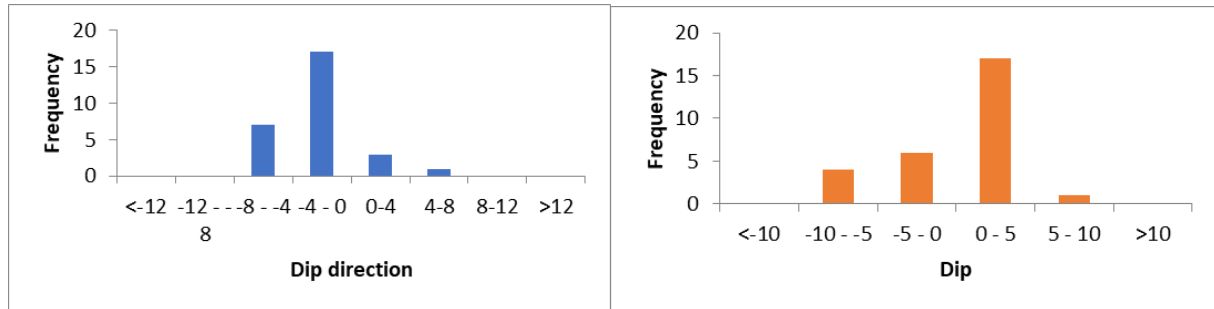


Fig. 3: Display of distribution of deviations in a) dip direction measurements b) dip measurements

From the results of the dip direction measurements, it can be concluded that all measurements (100.00%) fall within the range of $\pm 8^\circ$. Expressed as a percentage, given the possible azimuth range of 0° - 360° , this corresponds to a deviation of only 2.22%.

From the results of the dip measurements, it can be concluded that the majority of deviations fall within $\pm 5^\circ$. Expressed as a percentage, given the possible range of 0° - 90° , 82.14% of the measurements correspond to a deviation of 5.55%, while the remaining 17.86% exhibit a maximum deviation of 10.37%.

These findings suggest that the obtained statistical results fall within the range of normal deviations. Measurements of dip angle show a slightly higher proportion of maximum error, which may be attributed, at least in part, to the finer scale of subdivisions for dip angle values on the geological compass.

3.2. Regression analysis

To evaluate the relationship between the values of the measured elements obtained by both methods, a regression analysis was performed. This type of analysis enables the research results to be expressed in terms of an analytical relationship or equation. The least squares method was applied as the most suitable approach for establishing the regression dependence.

The coefficient of determination (R^2) was used as an indicator of the strength of the relationship between the variables. The reliability of the regression model is directly related to the magnitude of R^2 , which ranges from 0 to 1. The following criteria are commonly applied:

$R^2 < 0.3$: negligible dependence;

$0.3 \leq R^2 < 0.5$: weak correlation;

$0.5 \leq R^2 < 0.7$: moderate correlation;

$0.7 \leq R^2 < 0.9$: strong correlation;

$R^2 \geq 0.9$: very strong correlation.

Thus, higher R^2 values indicate a stronger relationship between the compared variables. Figure 4 present the regression analyses for all and average measured values obtained with both methods.

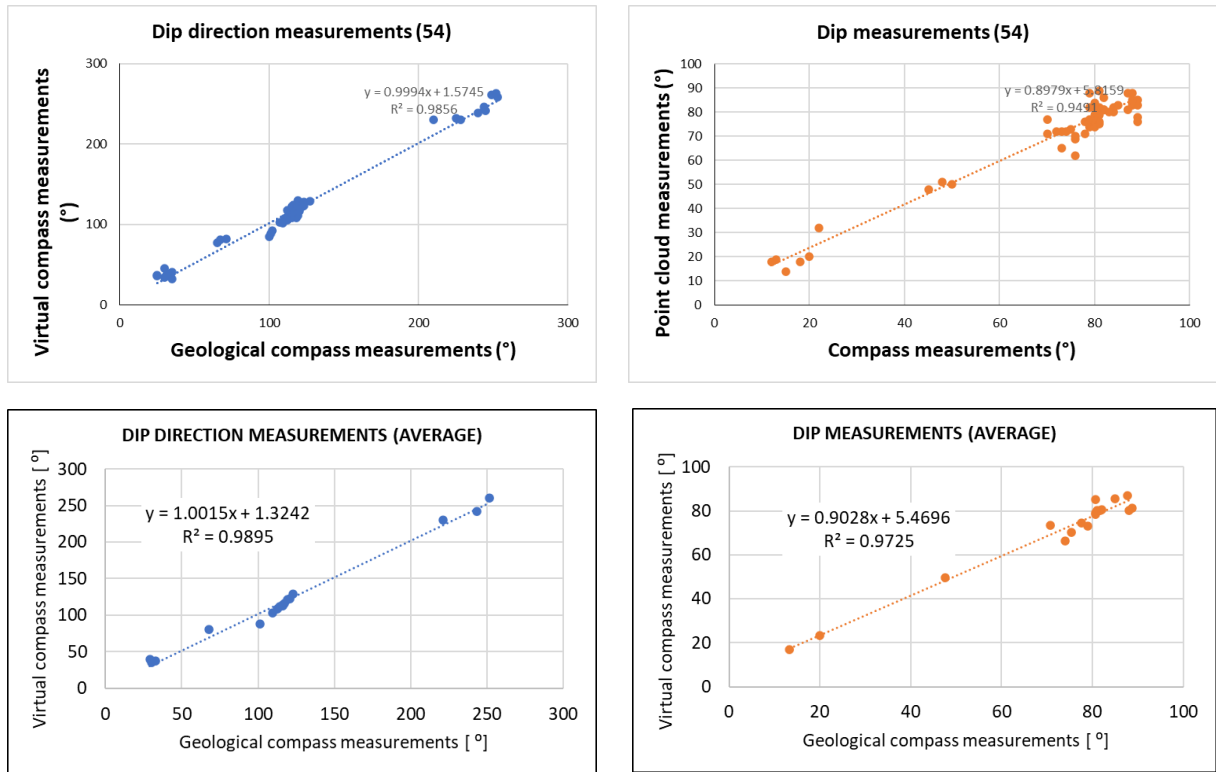


Fig. 4: Regression analysis from a) all dip direction measurements b) all dip measurements c) average dip direction measurements d) average dip measurements

Based on the results, it can be concluded that there is a strong dependence between the dip and dip direction values acquired by the two methods. Specifically, the correlation coefficients are as follows:

For all individual measurements: $R^2 = 0.9971$ for dip direction and $R^2 = 0.9192$ for dip angle.

For the average values: $R^2 = 0.9993$ for dip direction and $R^2 = 0.9501$ for dip angle.

These results clearly demonstrate a very strong correlation between the two approaches, confirming the reliability of smartphone-based LiDAR scanning as a valid alternative to traditional geological compass measurements.

3.3. Bland-Altman plot

A Bland–Altman plot is a graphical method used to compare two measurement techniques by plotting the differences between the two methods against their averages. This approach allows for the identification of any systematic bias and provides an assessment of agreement between methods, while also highlighting potential discrepancies.

The principle of the method is straightforward: the X-axis represents the mean of the two measurements, and the Y-axis represents the difference between them. The resulting chart can reveal anomalies; for instance, if one method consistently produces higher values, the data points will appear predominantly above or below the zero line [10] (Fig. 5). In the plots presented here, each blue dot corresponds to the difference between two measurements plotted against their average. The red line indicates the mean difference, representing the average bias between the two methods. A mean difference close to zero suggests negligible bias. The upper confidence limit is shown as a blue line and the lower confidence limit as a yellow line, both defined as the mean difference ± 1.96 times the standard deviation of the differences.

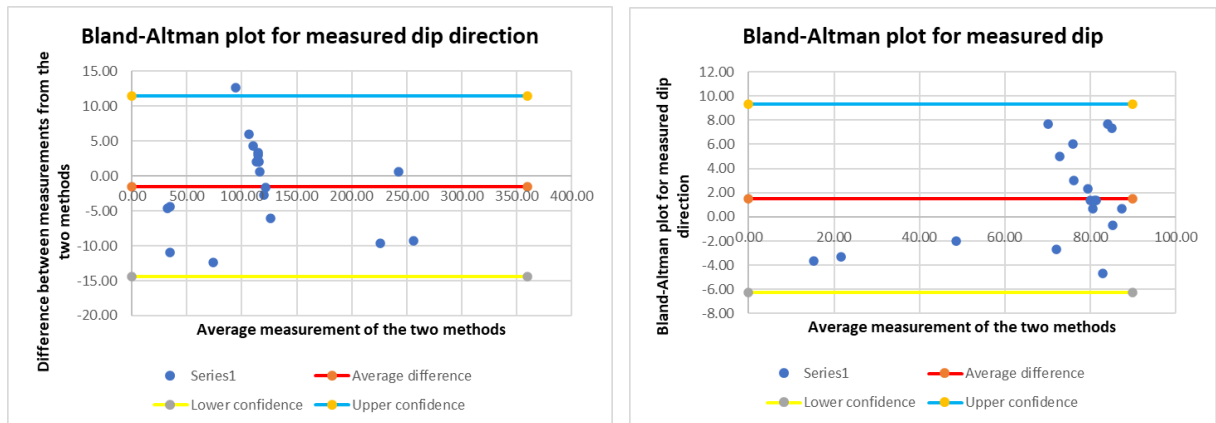


Fig. 5: Bland-Altman plot for the measured in a) dip direction b) dip

For both dip direction and dip angle, the majority of data points lie within the limits of agreement, which demonstrates a high level of consistency between the two methods. While a few points appear near or outside the limits of agreement, these outliers may be attributed to measurement errors, extreme values, or other influencing factors. Overall, the plots indicate that the two measurement techniques generally agree well, with most differences falling within the expected range. The overall agreement is strong, confirming that the methods can be used interchangeably for the majority of measurements.

3.4. Display on a stereogram

Doing the analysis, we must bear in mind that together, the dip and dip direction measurements provide a complete description of the orientation of the geological feature. They cannot be condensed into a single number because they represent two distinct aspects of the feature's geometry.

One way to represent the dip and dip direction together is to show the maximum of poles on stereograms using the software Dips (Fig. 6).

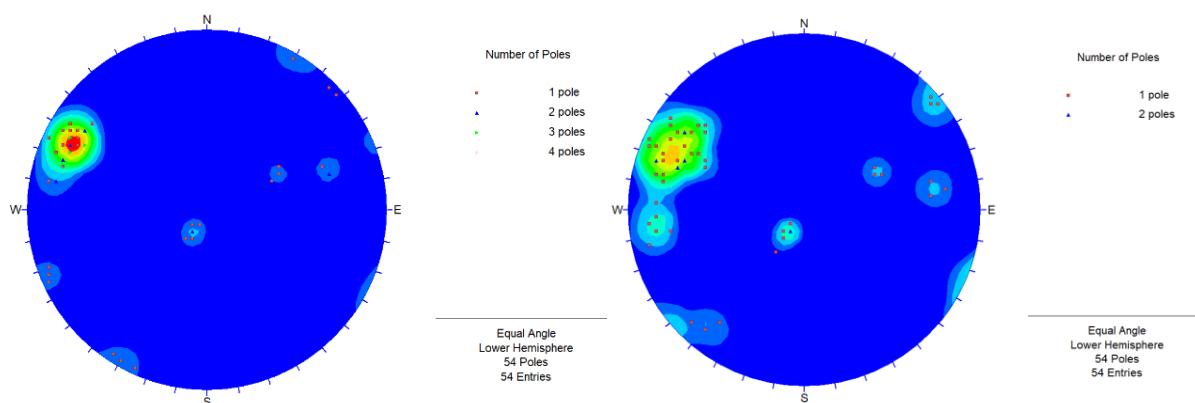


Fig. 6: Maximum of the poles in a) geological compass b) virtual compass

From the above, it can be concluded that the resulting poles obtained with geological and virtual compass coincide quite well.

5. CONCLUSIONS

This study explored the potential of low-cost structural geological data collection using modern technology, in this case, the iPhone 15 Pro. Overall, it can be emphasized that the data obtained with this new technology are highly consistent with those measured by an experienced geologist using a traditional geological compass.

The variations in measurements acquired with the geological compass and the virtual compass tool demonstrated very similar trends. The 3D point cloud generated with the iPhone accurately captured the terrain conditions, as validated by classical geological compass measurements. The deviations observed between the two methods remained within narrow margins, indicating a high level of compatibility and reliability.

Given the rapid pace of technological development, it is reasonable to assume that such modern tools will increasingly complement, and in certain cases even replace, traditional methods of structural data collection. Nevertheless, classical field techniques will remain indispensable, particularly for validation and cross-checking purposes. An important advantage of smartphone-based LiDAR scanning is that data are stored in a clear, reusable, and visually accessible format, allowing repeated analyses over time—unlike traditional field measurements, which are limited by site accessibility, excavation activities, or natural modifications of the outcrop.

At the same time, it must be stressed that this new method should be applied with caution. Proper interpretation of results requires a strong geological background and a sound understanding of the processes that shape rock mass behaviour. Without such expertise, even precise digital data may lead to misinterpretation.

Based on the results of this research, it can be concluded that smartphone-based LiDAR scanning represents a promising tool for the monitoring and characterization of road slopes. The ability to rapidly capture 3D point clouds of outcrops and road cuts with minimal equipment and cost is particularly advantageous in the context of road engineering, where slope stability is a critical safety concern. The high correlation between smartphone-derived measurements and traditional compass-based data indicates that this approach can be reliably used for preliminary surveys, periodic monitoring, and documentation of slope conditions. Such an accessible technology has the potential to significantly improve routine slope inspections, enabling engineers and geologists to identify hazardous zones and track changes over time without relying exclusively on expensive TLS equipment.

6. REFERENCES

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