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Road Damage Identification Using a Combination of UAV Quadcopter Technology and Subgrade Investigation

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ABSTRACT

Good road infrastructure is essential for traffic safety. However, more than 60% of roads in developing countries are in poor condition. As a developing country, Indonesia has 540,000 kilometers of roads, of which 40% are still in poor condition. Fast identification is needed to handle road damage. This research aims to identify road damage quickly using Unmanned Aerial Vehicle (UAV) and subgrade investigation through Dynamic Cone Penetrometer (DCP) testing. This study employs an experimental method, where the results of UAV aerial imagery are digitally processed using Agisoft Metashape and ArcGIS software with polygon analysis. Subgrade testing was conducted using DCP to measure the California Bearing Ratio (CBR) value. A descriptive study analyzed the relationship between subgrade conditions and road damage affecting traffic safety. The results showed 114 damage points with five types of road damage with a total area of 1,564.93 m^2. UAV mapping accuracy using omission and commission tests reached 98.39%, indicating highly accurate data. The average subgrade CBR value only reached 1.44%, indicating very poor soil conditions. This condition contributes to road damage, including potholes, depression, and cracks. Road repairs and subgrade improvements are needed to prevent further damage and improve road safety.

1. INTRODUCTION

Good road infrastructure is essential for economic growth, social development, and sustainable mobility [1]. According to the World Economic Forum (WEF) report of 2023, countries with high-quality road infrastructure have significant competitive advantages, especially in logistics efficiency and transportation safety [2, 3], especially in terms of logistics efficiency and transportation safety [4]. Good roads enable faster delivery of goods and reduce accident risks for users. However, the report also highlights that developing countries face significant challenges in improving the quality of their road networks, as identifying and repairing roads takes a lot of time and money. This aligns with the author's research, which focuses on developing a more efficient method for detecting road damage using UAV (Unmanned Aerial Vehicle) technology. Many developing countries still face serious challenges related to road network maintenance, with more than 60% of roads in disrepair [5, 6]. The high rate of road damage not only hampers mobility and logistics efficiency but also increases the risk of traffic accidents. Indonesia, as a developing country with an area of 1,905 million km^2 stretching from Sabang to Merauke, has significant challenges in maintaining road infrastructure safety and quality [7]. Based on Indonesian government data from the Ministry of Public Works and Housing in 2022, about 40% of the total 540,000 kilometers of roads in Indonesia are damaged with varying degrees of damage, ranging from cracks to severe structural damage that threatens the safety of road users [7, 8]. The different levels of damage indicate the need to utilize technology for more targeted road monitoring and maintenance. Merauke Regency, one of the regions located in the eastern tip of Indonesia, is not free from this problem. According to a report by the local government of Merauke Regency in 2021, about 45% of the roads in the regency are in poor condition, with the most severe damage occurring on the main access roads connecting the city center with rural areas [8].

Conventional road damage identification methods that only rely on manual inspection using roll meter measurements on the road surface are no longer adequate because they are considered slow in identifying road damage [9, 10]. Quadcopter UAV technology offers a more efficient solution to monitor and identify road damage by air using the photogrammetry technique, which is a mapping technique through aerial photographs [11-13]. The advantages of UAV technology are that it can produce detailed, accurate, and fast visual data over a large area, compared to conventional methods that rely on manual inspection in the field. In addition, combining photogrammetric results with subgrade Analyzed using a Dynamic Cone Penetrometer (DCP) makes identification more effective by understanding the structural soil factors behind road damages.

The main variables investigated in this study include accuracy testing with the metrics of omissions and commissions, road damage classification based on UAV data, and subgrade conditions based on DCP investigation results [14, 15]. UAV data allows visual classification of road damages, e.g., 5 cm/pixel means that 1 pixel in the image equals 5 cm in actual size [16], which is then compared with subgrade measurements. Based on research on UAVs conducted by Arinah et al. [17, 18], UAVs have more than 90% accuracy in detecting road damage. However, there is still a weakness in terms of false positives, which reach 10%, which shows the importance of accuracy testing. On the other hand, subgrade testing with DCP provides data related to soil strength and stability with The CBR (California Bearing Ratio) index as the primary benchmark [19]. Soils with a CBR below 3% often indicate a high potential for structural damage, particularly under heavy vehicle loads [20].

Most research on road damage only focuses on one aspect, be it road damage sensing using UAVs or soil condition analysis using Geotechnical Methods. This approach often results in a fragmented understanding, making it challenging to identify the relationship between the deterioration of the road surface and the underlying soil conditions [13, 14, 21, 22]. Combining the methods of road surface defect identification and subgrade investigation is not only in line with current trends in technology-based road infrastructure management but also broadens the scope of research by offering a more applicable holistic approach to road maintenance. Only a few studies have integrated both methods to analyze road damage comprehensively. In this context, the novelty of this research lies in the unique combination of quadcopter UAV and subgrade soil testing via DCP. This method offers a new, more comprehensive approach to understanding the factors contributing to road deterioration in terms of the road surface and the underlying soil conditions [23].

This research aims to develop a more efficient and accurate road damage identification method by combining quadcopter UAV technology and subgrade investigation through DCP. This research also evaluates the accuracy of road damage detection through omission and commission tests, classifies road damage types based on UAV data, and analyzes road subgrade conditions based on DCP test results.

The structure of this article is organized into several sections. The first section is the Background section, which outlines the issues related to road damage and the urgency of this research. The second section is Methodology, which explains the technical approach used in the study, including data collection using UAVs and DCPs. The third section is Results and Discussion, which presents the research findings, such as the classification of road damage based on UAV imagery and the results of the subgrade investigation using DCP. The last section is the Conclusion, which summarizes the main results of the research and provides recommendations for road infrastructure maintenance in Merauke.

2. RESEARCH METHODS

This research employs an experimental method, processing UAV aerial imagery digitally using Agisoft Metashape and ArcGIS software with polygon analysis. This research also uses quantitative descriptive analysis aimed at identifying and measuring road damage using UAV Quadcopter technology and analyzing the stability of the road base soil through investigation with a Dynamic Cone Penetrometer (DCP) [11]. The data from both methods were analyzed to obtain descriptive information on road damage and subgrade conditions. The research design also involved measuring the accuracy of the analysis results using the omission and commission method [24].

2.1 Location and time of research

This study was conducted on the Waninggap Say Village Road, Merauke Regency. The research focused on 500 meters of damaged road surface at coordinates 8°20'57.3"S 140°30'22.9"E. The research was conducted over two months, from May to July 2024. The location of this study can be seen in Figure 1, which shows the area that is the object of research as well as a sample of road conditions.

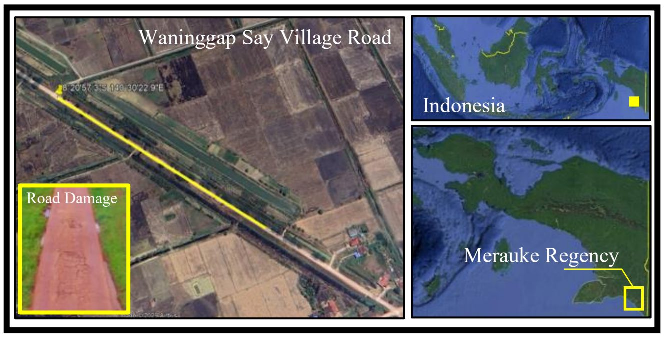


Figure 1. Research location at Waninggap Say Village Road, Merauke Regency, Indonesia

In the first month, preparations such as equipment testing and installing the Ground Control Points (GCP) for image capture using UAV. GCP were installed at several strategic points along the road to ensure aerial image accuracy. Next, a soil investigation was conducted at the same location using the Dynamic Cone Penetrometer (DCP) method. This investigation measured subgrade strength beneath the damaged road. Field data collection for aerial imagery was conducted in June using a Quadcopter UAV with planned flights along the road section. Simultaneously, DCP soil testing was conducted at designated points, focusing on severely damaged road sections. Data fusion and analysis of the UAV photogrammetry and DCP soil investigation were conducted in July [25].

2.2 Research data

This research utilizes two main data sources from aerial sensing using a UAV Quadcopter and soil investigation using a Dynamic Cone Penetrometer (DCP). These data complement each other to provide a comprehensive view of the damaged road surface and subgrade strength [11]. Quadcopter UAV data in the form of aerial images obtained through Quadcopter UAV flights with The Autel Evo II Pro V3 brand operating along 500 meters of the Waninggap Say Village Road section, which is the object of research. This data is crucial for visualizing road surface damage. The UAV is equipped with a 6K high-resolution camera capable of capturing details of damage to the road surface, such as cracks, holes, deformations, and other damage [26]. Soil testing data were obtained from subgrade testing at six points spaced 100 meters apart using a Dynamic Cone Penetrometer (DCP). This test aimed to evaluate the strength of the subgrade that supported the road. DCP provides CBR values, indicating soil strength and bearing capacity for traffic loads. Tests were conducted at locations corresponding to the UAV imagery to evaluate how subgrade visible road damage [27].

2.3 Data collection method

Visual data were collected using an Autel Evo II Pro V3 UAV equipped with a 6K camera and stable flight for accurate road damage mapping. The UAV was operated using the Auto Explorer app on the smart controller, enabling automatic and precise flight mission planning. The drone-generated imagery uses Ground Sampling Distance (GSD) as a measure of spatial resolution, which indicates the actual distance on the ground surface represented by a single pixel. The first step in UAV data collection is to design the flying mission [26]. The flying mission used a rectangular model to map a 500-meter road section. The second stage is the flight mission setting, which includes determining the flight altitude of 50 meters above the road surface and the drone travel speed reaches 30 m/s. front overlap at 90%, and side overlap at 85%. and spatial resolution (GSD) reaches 1.17 cm/pixel so that the resulting image has good quality and can be optimally combined through the photogrammetry process through Agisoft Metashape and ArcGIS software [28]. Ground Sampling Distance (GSD) is a measure of spatial resolution in drone-generated imagery. It indicates the actual distance on the ground represented by one pixel in an aerial photograph. For example, a GSD of 1.17 cm/pixel means that each pixel in the image represents an area of 1.17 cm on the ground.

A flying altitude of 50 meters is the ideal distance for aerial photography because it can maintain the level of detail of the road surface up to a resolution of 1.17 cm/pixel, which is the value of GSD. If the altitude exceeds 50 meters, the detail quality will be reduced due to the increased GSD value. On the other hand, if the altitude is too low, there is a greater risk of disrupting the image capture due to obstructions such as vegetation or buildings around the road. A drone flight speed of 30 m/s allows for faster time efficiency in surveying. At this speed, the drone can still maintain its position, stability, and the quality of the mapping results.

Once the visual data from the UAV was obtained, the next step was to investigate the subgrade at the same location using a Dynamic Cone Penetrometer (DCP). This DCP test aims to measure the strength of the subgrade, which plays an important role in determining the carrying capacity of the road against traffic loads. The DCP data collection were collected at six points along the damaged road section. Tests were conducted at intervals of every 100 meters along the road. At each point, the DCP tool was used to penetrate the soil to a depth of up to 90 degrees. Before DCP testing, a test pit was excavated at each test point. This test pit was used to examine the profile and condition of the soil layers directly. The test pits were excavated to depths of 0.5–1 meter, providing detailed information on soil stratification at the site. Test pit excavation includes visual information on moisture content, specific gravity, Atterberg limits, and sieve analysis. This tool drops a particular load on a penetration rod, and the resulting penetration depth is recorded each time the load is lowered. The data obtained is penetration depth values at certain intervals, which are then processed to obtain the California Bearing Ratio (CBR) value. The CBR values obtained from DCP testing indicate the strength of the subgrade at those points. The higher the CBR value, the stronger the subgrade withstanding the load, and vice versa. This data will then be synchronized with road damage data obtained from UAV imagery to determine whether subgrade strength and the level of road damage are related [15, 27].

2.4 Data analysis method

This research divides data analysis into two parts, namely UAV photogrammetric data for identifying road damage and DCP soil testing data for evaluating subgrade strength. UAV data analysis involved processing aerial imagery of damaged roads using photogrammetric methods. This data was processed through several stages using Agisoft Metashape software to produce an accurate photogrammetric model. After the model is formed, the next step is calculating the damaged area using ArcGIS and testing accuracy with the Omissions and Commissions method using Eq. (1) [15,18]:

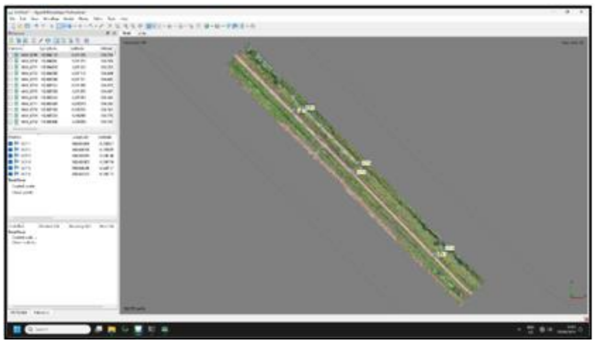
$$\text{Accuracy}=\left[1-\left[\frac{\Delta}{Field}\right]\right]\times 100\% \quad (1)$$

DCP data were used to assess subgrade strength the damaged road section. DCP results provide CBR values, indicating soil strength against traffic loads. CBR calculation can be used in Eq. (2) below [19, 27]:

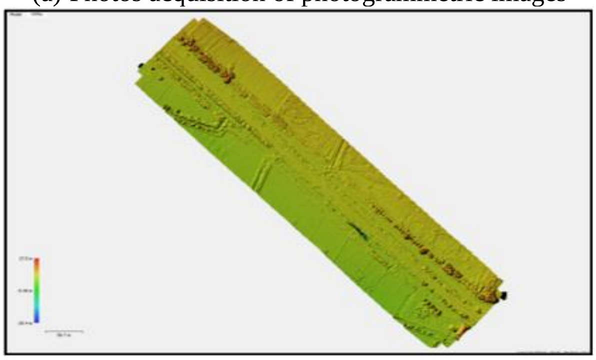
$$CBR_{STA}=\left\{\frac{h_1\sqrt[3]{CBR_1}+\ldots+h_n\sqrt[3]{CBR_n}}{\sum_{i=1}^{n}h_i}\right\}^3 \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Aerial photo acquisition and data processing



(a) Photos acquisition of photogrammetric images



(b) Digital Elevation Model (DEM) from photogrammetric imagery

Figure 2. Digital representation of aerial imagery

Aerial photos were taken from 08:00 to 12:00 WIT, considering weather conditions. This time was chosen because clouds had not yet formed, and shadows from the sun were visible on large objects. The coordinate system used in road damage mapping is WGS 84 or UTM zone 54S. After the aerial photos were collected, the next step was to process the data using Agisoft Metashape software. The software processes UAV aerial photos into orthophoto mosaics to identify road damage on Waninggap Say Village Road. Orthophotos were created in Agisoft Metashape through stages such as photo import, alignment, optimization, and dense point cloud construction. The resulting 3D models and texture models are shown in Figure 2(a) and DEM (Digital Elevation Model) in the creation of orthophotos. The resulting orthophoto provides high-fidelity data for road condition analysis, as shown in Figure 2(b).

3.2 Damage measurement and accuracy test

Road damage was measured in ArcGIS using the polygon generation method. Each road damage identified from the orthophoto is processed by drawing a polygon corresponding to the damage boundary on the road surface. Once the polygon is formed, the area of road damage can be calculated automatically by the software based on the area enclosed by the polygon. This method provides accurate results in identifying the type and extent of road damage so that road damage can be analyzed, as shown in Figure 3.

Figure 3. Classification of road damage at STA 0+000 to 0+100

Road damage measurements were conducted from STA 0+000 onward based on polygon data. After polygons were created and classified with different colors, the total damage area was calculated based on these classifications. The following are the results of the road damage classification along with the area of damage based on the summation results, which can be shown in Table 1.

Table 1 shows the classification of road damage in Segment 1 (STA 0+000 to STA 0+100). The types of damage include Potholes (yellow polygon, 96.87 m²), Depressions (green polygon, 98.69 m²), Longitudinal Cracks (pink polygon, 17.3 m²), and Transverse Cracks (black polygon, 8.076 m²). Segment 1 (STA 0+000 to STA 0+100) includes 4 types of damage with a total of 23 instances and a cumulative area of 220.93 m².

The findings of road defects in Segment 1 have implications for road safety and maintenance by increasing the risk of accidents for motorists, mainly due to Potholes and Depressions that can cause loss of control. From a maintenance perspective, these significant defects require immediate repair to prevent further damage and reduce long-term repair costs.

Subsequent damage calculations were performed on road sections from STA 0+100 to STA 0+500, covering Segment 2 (STA 0+100 to STA 0+200) to Segment 5 (STA 0+400 to STA 0+500). The same method was used to measure and calculate the damage area in each segment using polygons. The following is a recapitulation table in all segments:

Table 1. Classification of road damage in segment 1, STA 0+000 to STA 0+100

No.	Type of Damage Classification	Polygon	Quantity	Area (m²)
1	Potholes		5	96.87
2	Depression		6	98.69
3	Longitudinal crack		1	17.30
4	Transverse cracks		11	8.07
	Total		23	220.93

Table 2. Recapitulation of road damage STA 0+000 to STA 0+100

No.	Type of Damage Classification	Quantity	Area (m²)
	Segment 1: STA 0+000 - 0+100		
1	Potholes	5	96.87
2	Depression	6	98.69
3	Longitudinal crack	1	17.30
4	Transverse cracks	11	8.07
	Total	23	220.93
	Segment 2: STA 0+100 - 0+200		
1	Potholes	1	13.62
2	Depression	2	233.82
3	Transverse cracks	15	6.12
4	Other cracks	1	42.18
	Total	19	295.74
	Segment 3: STA 0+200 - 0+300		
1	Potholes	3	112.88
2	Depression	3	141.53
3	Transverse cracks	15	7.19
4	Other cracks	2	49.83
	Total	23	311.43
	Segment 4: STA 0+300 - 0+400		
1	Potholes	2	267.04
2	Depression	1	133.20
3	Transverse cracks	6	1.14
	Total	9	401.38
	Segment 5: STA 0+400 - 0+500		
1	Potholes	6	187.05
2	Depression	7	133.20
3	Transverse cracks	25	6.76
4	Other cracks	2	8.44
	Total	40	335.45
	Grand Total	114	1,564.93

Table 2 shows the result of identifying road damage in five segments, from STA 0+000 to STA 0+500. Segment 1 recorded 23 damages covering 220.93 m², while Segment 2 had 19 damages covering 295.74 m². Segment 3 showed 23 damages totaling 311.43 m², and Segment 4 had the largest damage area of 401.38 m² from 9 damages. Segment 5 recorded 40 damages totaling 335.45 m². The total number of damages was 114, with 5 types of damages and a total area of 1,564.93 m², indicating a significant level of damage along the road sections studied. The extent of this damage poses a serious risk to road users, increasing the likelihood of accidents.

The total area of damage reached 1,564.93 m² of the total study area of 2,000 m^2 or equivalent to 78% of the damage, indicating a severely damaged road condition and potentially endangering user safety. The damage on Waninggap Say

Village Road includes 5 types that affect vehicle stability, particularly for two-wheeled and heavy vehicles vulnerable to surface deformation. This condition indicates the need to prioritize road improvements to improve road user safety.

The predetermined polygon points were validated using the omissions method to evaluate measurement accuracy. The omissions method identifies errors from detected (commission) or undetected (omission) points in the orthomosaic image. With this method, the evaluation becomes more comprehensive and provides a clear picture of the accuracy and suitability of the orthomosaic in reflecting the actual conditions on the ground. The following exposures are the results of the orthophoto accuracy test using Eq. (1) based on the geometric comparison of road width between field measurements and UAV image interpretation measurements.

$$\text{Accuracy} = \left[1 - \left[\frac{\Delta}{Field}\right]\right] \times 100\%$$

$$\text{Accuracy} = \left[1 - \left[\frac{0.12}{4.96}\right]\right] \times 100\%$$

$$\text{Accuracy} = 97.58\%$$

Table 3. Recapitulation of accuracy test with interpretation and field comparison

No.	Stationing (STA)	Measurement Omissions - Commission		Δ	Accuracy (%)
		Interpretation (m)	Field (m)		
1	STA 0+000	4.84	4.96	0.12	97.58
2	STA 0+100	4.83	4.94	0.11	98.17
3	STA 0+200	5.01	5.07	0.06	98.82
4	STA 0+300	4.97	5.04	0.07	98.61
5	STA 0+400	5.02	4.94	0.08	98.38
6	STA 0+500	5.04	4.98	0.06	98.80
Average					98.39

The counting results in Table 3 using the omission and commission method show that the accuracy of road damage identification using UAV image data reaches 98.39%, which is a high precision. UAV methods have proven highly effective in mapping road conditions, enabling early detection of defects to prevent accident risks and accelerating data-driven decision-making to optimize road maintenance.

The accuracy of the UAV mapping shows excellent results, but the potential error of 1.61% still needs to be evaluated to maintain data quality. This error can be caused by several technical factors, such as inaccuracies in image processing, distortions in the UAV camera, and inaccurate placement of Ground Control Points (GCP). In addition, environmental factors such as wind, shadows or inconsistent lighting during image capture can also contribute. Therefore, understanding and mitigating these sources of error is essential to ensure accuracy remains high so that research results remain valid and can be used as a basis for decision-making.

3.3 Subgrade investigation

The tests were conducted to investigate the road's subgrade by conducting a pit test that obtained data on soil properties, DCP (Dynamic Cone Penetrometer), and CBR (California Bearing Ratio) values for a length of 500 meters. Soil properties testing aimed to obtain subgrade soils' physical and mechanical characteristics in supporting road infrastructure. Through a series of tests such as moisture content, specific gravity, Atterberg limits, and sieve analysis, the composition and behavioral characteristics of subgrade soils under various conditions were determined. The results of these tests are essential to evaluate the bearing capacity of the soil with soil classification according to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) according to the soil characteristics. The following are the results of the Pit Test to determine the value of soil properties.

Table 4. Soil properties test results

No.	Testing	Symbol	Value	Units
1	Moisture content	WC	24.80	%
2	Specific gravity	WG	2.64	-
3	Atterberg limit			
	Liquid limit	LL	50.24	%
	Plastic limit	PL	43.40	%
	Plasticity index	PI	6.84	%
4	Sieve analysis			
	Gravel		0.40	%
	Sand		10.28	%
	Silt		78.32	%
	Clay		11.00	%

Soil Classification

No.	Classification System	Group	Dominant Material
1	Unified Soil Classification System (USCS) classification	MH	Non-organic silt or haul sand, elasticity silt
2	American Association of State Highway and Transportation Officials (AASHTO) classification	A-5	Silty soil

From the soil property test results shown in Table 4 on the Waninggap Say Village Road section, it can be concluded that the soil moisture content is 24.80%, with a specific gravity of 2.64. Regarding Atterberg limits, the soil has a liquid limit (LL) of 50.24%, a plastic limit (PL) of 43.40%, and a plasticity index (PI) of 6.84%, indicating limited deformation ability. Sieve analysis showed that the soil composition consists of 0.40% gravel, 10.28% sand, 78.32% silt, and 11.00% clay. According to the USCS, the soil is classified as MH, which represents non-organic silt or fine sand with elastic properties. According to AASHTO, the soil falls under the A-5 classification, which indicates silty soil and is classified as fine-grained soil, with the results of the sieve test passing a No. 200 filter with 88.71%. The dominant silt composition (78.32%) and the elastic nature of this soil increase the risk of deformation in the subgrade layer, especially under heavy traffic loads. This condition demands special attention in road design and maintenance, including subgrade reinforcement and a sound drainage system to prevent further damage and ensure the safety of road users.

DCP testing is a rapid method for evaluating the strength of subgrade and road foundation layers using a dynamic cone penetrometer. It can also serve as an alternative method if field CBR testing cannot be performed. The test provides the strength of the material layer to a depth of 90 cm below the existing surface without excavating to the desired depth for the reading. The following is the calculation of the CBR value using Eq. (2) and a recapitulation of the Dynamic Cone Penetrometer test data:

$$CBR_{STA\ 0+000} = \left\{\frac{h_1 \sqrt[3]{CBR_1} + \ldots + h_n \sqrt[3]{CBR_n}}{\sum_{i=1}^{n} h_i}\right\}^3$$

$$CBR_{STA\ 0+000} = \left\{\frac{1{,}101}{987}\right\}^3$$

$$CBR_{STA\ 0+000} = 1.39$$

Table 5. Recapitulation of dynamic cone penetrometer test results

No.	Stationer (STA)	CBR (%)
1	0 + 000	1.39
2	0 + 100	1.51
3	0 + 200	1.89
4	0 + 300	1.21
5	0 + 400	1.06
6	0 + 500	1.55
Average		1.44

From the results of DCP testing on the Waninggap Say Village Road section, as shown in Table 5, the subgrade in this section has an average CBR value of 1.44%, which is less than 3%. Based on these results, we can state that the CBR value of the Waninggap Say Village Road section is very low, and it is necessary to strengthen the subgrade, especially in supporting the construction of road sections. Subgrade reinforcement is required through soil stabilization or subgrade material improvement to support traffic loads and improve driving safety.

4. CONCLUSIONS

The results of identifying road damage on the Waninggap Say Village Road section show 114 damage points with five types of damage, covering a total area of 1,564.93 m², which can endanger the safety of road users. The accuracy of road damage identification using the omission-commission test reached 98.39%, indicating high effectiveness and precision in mapping road conditions. The number of damage points and the extent of the damage can be directly attributed to the poor subgrade conditions in the area. Based on DCP testing, the subgrade at this location has a very low CBR value, with an average of only 1.44%. Very low CBR values indicate that the subgrade is very poor and unable to support traffic loads properly. This explains why the damage identified along the road segment is extensive and varied, including potholes, depressions, longitudinal cracks, transverse cracks, and other cracks on the road surface. The subgrade on this road segment requires stabilization before road repair or reconstruction. If repairs are only made to the road surface, the road will continue to experience damage due to the inability of the soil to withstand the load. This condition increases the risk of accidents and threatens the safety of road users.

Some assumptions in this study need to be noted, such as that the UAV mapping data used is highly accurate. However, environmental factors such as changes in lighting or wind may cause slight distortions. In addition, the CBR test results represent the subgrade conditions in the study area at some points, although soil conditions may still vary along the road section. This study also considers that the distribution of road damage detected by the UAV reflects the overall condition of the defects. However, there is potential for damage in areas not covered by the mapping, especially defects that are less than the GSD value of 1.17 cm/pixel. Finally, this study focused on the relationship between road deterioration and subgrade conditions without considering other factors, such as extreme weather or inadequate maintenance, that could also contribute to deterioration. These assumptions need to be focused on in a more in-depth analysis as they may affect the accuracy and generalizability of the research findings.

Based on the research findings, the following steps that need to be investigated are subgrade stabilization methods to overcome low CBR values and road damage monitoring using UAVs integrated with remote sensing systems that can create automatic polygons as road damage markers. Research should also examine the influence of environmental factors, such as rainfall, on road damage and the importance of regular maintenance to prevent further damage.

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NOMENCLATURE

A-5	Silty soil
CBR	California Bearing Ratio
DCP	Dynamic Cone Penetrometer
LL	Liquid limit
MH	Non-organic silt or haul sand, elasticity silt
PI	Plasticity index
PL	Plastic limit
STA	Stationer
UAV	Unmanned Aerial Vehicle
WC	Moisture content
WG	Specific gravity

Greek symbols

Δ	Difference in measurement values Omissions - commissions