E-ISSN: 2964-6219, P-ISSN: 2964-6200
Volume 5 Number 1 February 2027.
pp: 152-161. DOI: https://doi.org/10.58477/cj.v5i1.614.

Computer Journal

RESEARCH ARTICLE Open Access

Development and Feasibility Evaluation of AR-GeoHazard for Slope Gradient Visualization in Pagar Alam

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Article History
Received: 29 October 2026.
Revised: 31 October 2026.
Accepted: 14 November 2026.
Available Online: 5 December 2026
Published: 1 February 2027.

Funding Information
Institut Teknologi Pagar Alam.

Abstract
Accessible terrain information is essential for supporting geospatial literacy and disaster education in mountainous environments. This study aimed to develop and evaluate AR-GeoHazard, an Android application for slope-gradient visualization in Pagar Alam, Indonesia. A research-and-development approach followed the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) framework, incorporating prototyping for application refinement. The application integrates elevation profiles, three-dimensional terrain visualization, smartphone-assisted slope observations, recording features, and interpretive guidance. Evaluation comprised 40 black-box test scenarios, assessments by two experts, task-based testing and System Usability Scale (SUS) questionnaires involving 20 users, and comparisons with geographic information system (GIS)-derived slope classes at 30 reference points. The evaluation results showed a functional success rate of 95.00%, an expert assessment score of 91.60%, a task-completion rate of 94.00%, a mean SUS score of 86.75, and GIS classification agreement of 93.33%. The weighted feasibility index reached 92.19, meeting the study-defined criteria for high feasibility. However, two functional failures, two classification mismatches, and ambiguous safety labels require further investigation. These findings support the continued development of AR-GeoHazard as an educational terrain-visualization tool, while sensor accuracy, spatial registration, and learning effectiveness require dedicated validation.

Keywords: Augmented Reality; Slope-Gradient Visualization; Feasibility Evaluation.

Abstrak
Informasi kondisi medan yang mudah dipahami sangat diperlukan untuk mendukung literasi geospasial dan pendidikan kebencanaan di wilayah pegunungan. Penelitian ini bertujuan mengembangkan dan mengevaluasi kelayakan AR-GeoHazard, sebuah aplikasi Android untuk visualisasi kemiringan lereng di Pagar Alam, Indonesia. Penelitian ini menggunakan pendekatan penelitian dan pengembangan dengan kerangka Analysis, Design, Development, Implementation, dan Evaluation (ADDIE), yang disertai pembuatan prototipe untuk penyempurnaan aplikasi. Aplikasi ini mengintegrasikan profil elevasi, visualisasi medan tiga dimensi, pengamatan kemiringan lereng berbantuan ponsel pintar, fitur pencatatan pengamatan, dan panduan interpretasi. Evaluasi mencakup 40 skenario pengujian kotak hitam (black-box), penilaian oleh dua ahli, pengujian berbasis tugas dan kuesioner System Usability Scale (SUS) terhadap 20 pengguna, serta perbandingan kelas lereng dengan hasil sistem informasi geografis (SIG) pada 30 titik referensi. Hasil evaluasi menunjukkan tingkat keberhasilan fungsional sebesar 95,00%, skor penilaian ahli sebesar 91,60%, tingkat penyelesaian tugas sebesar 94,00%, rerata skor kebergunaan (SUS) sebesar 86,75, dan kesesuaian klasifikasi lereng SIG sebesar 93,33%. Indeks kelayakan tertimbang mencapai 92,19 dan memenuhi kriteria sangat layak yang ditetapkan dalam penelitian ini. Namun, dua kegagalan fungsional, dua ketidaksesuaian klasifikasi, dan ambiguitas label keselamatan memerlukan pemeriksaan lebih lanjut. Temuan ini mendukung pengembangan lanjutan AR-GeoHazard sebagai media visualisasi medan untuk edukasi, sedangkan akurasi sensor, keselarasan spasial, dan efektivitas pembelajaran memerlukan validasi khusus.

Kata Kunci: Realitas Tertambah; Visualisasi Kemiringan Lereng; Evaluasi Kelayakan.

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1. Introduction

Communicating terrain conditions clearly is essential for supporting geospatial literacy and disaster education in areas characterized by substantial elevation differences. In Pagar Alam, South Sumatra, Indonesia, the landscapes surrounding Mount Dempo provide a relevant setting for explaining the relationships among elevation, landforms, and slope gradients. Plantations and settlements occupy this varied terrain, creating a practical need for accessible representations of local topographic conditions. Mukti and Puspita (2019) identified the importance of accessible disaster information through their development of a mobile disaster information system for Pagar Alam. Building on this local context, mobile terrain visualization offers a promising means of connecting numerical slope information with recognizable landscapes and everyday observations. Slope gradient is a fundamental terrain attribute, but its interpretation requires a clear distinction between topographic description and landslide assessment. Ramli *et al*. (2026) and Rusk *et al*. (2022) explain that landslide susceptibility, hazard, and vulnerability assessments require multiple forms of spatial information rather than slope measurements alone. Similarly, Reichenbach *et al*. (2018) describe landslide susceptibility modeling as an analysis of relationships between landslide occurrence and multiple geoenvironmental conditions. Accordingly, a slope category should not be presented as a definitive indication that a location is safe or hazardous without considering other relevant environmental factors. Educational applications must therefore explain the meaning and limitations of their classifications to support informed interpretation and avoid unwarranted confidence in simplified labels. Geographic information systems (GIS) and digital elevation models (DEMs) provide a quantitative foundation for representing elevation, deriving slope gradients, and examining terrain morphology (Blackburn & Commander, 2026; Joost *et al*., 2026; Okegbola *et al*., 2026). Within a mobile interface, two-dimensional elevation profiles can illustrate height variations along a transect, while three-dimensional terrain models can support the exploration of landform geometry. Augmented reality (AR) introduces an additional possibility by integrating digital content with observations of the physical environment. However, Azuma (1997) identifies real-time interaction and three-dimensional registration as defining characteristics of AR, while studies on real-time two-dimensional-to-three-dimensional alignment emphasize that sensing and registration errors remain central technical challenges (Abumoussa *et al*., 2023; Ma *et al*., 2021). Consequently, the presence of a camera overlay or an interactive terrain model must be distinguished from demonstrated spatial alignment, and the provenance and processing of elevation data must remain traceable.

Research on educational AR provides a rationale for exploring interactive terrain visualization while also highlighting the need for careful evaluation. Akçayır and Akçayır (2017) report educational advantages associated with AR, including improved learning performance, alongside challenges related to usability and implementation. Within Indonesian geography education, Salsabila and Putra (2024) investigated AR-based visualization of volcanic processes, while Prayitno and Juwita (2023) examined AR learning materials in school geography. Although these studies support further investigation of interactive spatial representations, their findings do not establish the feasibility, measurement accuracy, or educational effectiveness of a different application. For AR-GeoHazard, the resulting evaluation need is to examine whether terrain visualization, smartphone-assisted slope observations, and interpretive guidance can be combined in a functional and usable application with clearly communicated limitations. To address this need, this study presents the development and feasibility evaluation of AR-GeoHazard, an Android application comprising DEM Data, AR Slope, Guide, and Exit menus. The application integrates elevation profiles, three-dimensional terrain visualization, slope-angle and percentage-gradient displays, observation recording, and explanatory guidance within a single mobile environment. Using an Analysis, Design, Development, Implementation, and Evaluation (ADDIE)-based development process supported by prototyping, the study examines functional performance, expert assessments, user-task completion, perceived usability through the System Usability Scale (SUS), and agreement with GIS-derived slope classes. Particular attention is given to the consistency between displayed angles and gradients, the correspondence between technical slope classes and interface labels, and the distinction between usability evidence and geospatial validation. The study contributes a multidimensional evaluation of a mobile terrain-visualization prototype intended to support geospatial literacy and disaster education, while reserving claims about sensor accuracy, learning gains, and landslide prediction for dedicated validation.

2. Methodology

This study employed a research-and-development (R&D) approach guided by the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) framework (Figure 1), with prototyping incorporated to support the iterative refinement of the AR-GeoHazard Android application. The analysis stage identified slope-information needs and DEM/GIS data requirements, while the design stage established the interface structure, visualization features, and slope-classification rules. During the development stage, these specifications were implemented through four main menus—DEM Data, AR Slope, Guide, and Exit—followed by implementation in functional and user-testing scenarios. The application adopted five operational slope classes: flat (0–8%), gentle (>8–15%), moderately steep (>15–25%), steep (>25–45%), and very steep (>45%), which were treated as terrain descriptors rather than definitive indicators of landslide hazard. The evaluation stage drew on prototype documentation and aggregate testing results covering 40 black-box test scenarios, assessments by two experts across 25 items using a five-point Likert scale, 20 users completing five tasks and a System Usability Scale (SUS) questionnaire, and 30 paired comparisons between application-generated and GIS-derived slope classes.

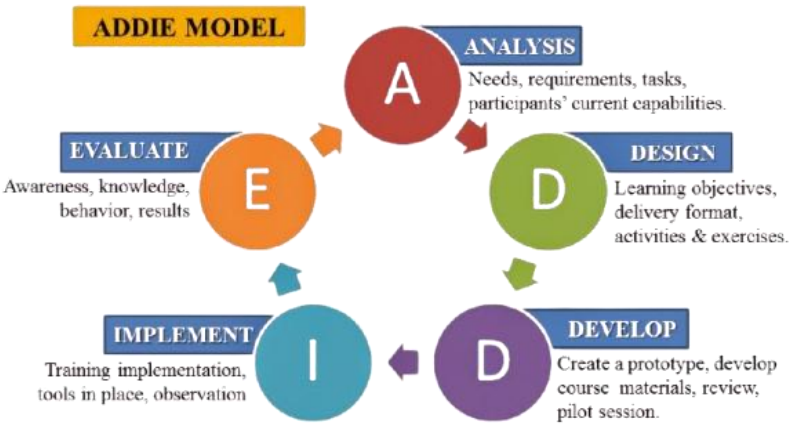


Figure 1. ADDIE framework for the development and feasibility evaluation of AR-GeoHazard

Application feasibility was evaluated across five dimensions: functionality (F), expert assessment (P), task completion (T), perceived usability (SUS), and geospatial classification agreement (G). Functionality, expert assessment, task completion, and geospatial agreement were each calculated as the observed score divided by its corresponding maximum or reference total, multiplied by 100%. Individual SUS scores were calculated by subtracting 1 from odd-numbered item responses and subtracting even-numbered item responses from 5, summing the adjusted values, and multiplying the total by 2.5; the mean across all respondents represented overall perceived usability on a 0–100 scale. The composite feasibility index (I) was then calculated using Equation (1):

$$I = 0.25F + 0.20P + 0.15T + 0.20SUS + 0.20G \quad (1)$$

This calculation applied predetermined weights alongside a study-specific "highly feasible" criterion requiring both the composite index and every component score to exceed 80. These numerical criteria were interpreted alongside functional failures, classification inconsistencies, and potentially ambiguous safety messages. Because the evaluation relied on aggregate test summaries rather than observation-level logs and raw spatial reference files, the analysis explicitly distinguished reported application feasibility from demonstrated sensor accuracy, spatial registration, or landslide-prediction capability.

3. Results and Discussion

3.1 Results

AR-GeoHazard was developed as an Android application comprising four main menus: DEM Data, AR Slope, Guide, and Exit (Table 1). The DEM Data menu presents elevation profiles and terrain visualizations, while the AR Slope menu displays smartphone-assisted slope observations. The Guide menu provides

operational instructions and explanatory material, and the Exit menu allows users to close the application through a confirmation dialog. The documented interface therefore integrates terrain exploration, slope observation, data recording, and interpretive guidance within a single mobile environment.

Table 1. Documented menus and functions of the AR-GeoHazard prototype

Menu	Documented functions
DEM Data	Profile selection, two-dimensional elevation charts, three-dimensional terrain visualization, coordinate information, and data-export options
AR Slope	Camera/sensor display, slope angle, percentage gradient, spirit-level indicator, display freezing, observation saving, and history
Guide	Operating instructions, explanations of DEM and slope concepts, slope categories, and mitigation information
Exit	Confirmation dialog for cancelling or closing the application

The DEM Data menu presents topographic information associated with several locations in Pagar Alam, including Mount Dempo, tea plantations, Curup Embun, and urban areas. Its initial screen allows users to select an elevation profile for further exploration (Figure 2), while the visualization screens include both a two-dimensional profile showing elevation changes along a selected transect and a three-dimensional representation of terrain morphology (Figure 3). In addition, the menu displays options for exporting data in GeoJSON, CSV, and text-report formats (Figure 4), with the application documentation referring to the retrieval of elevation values for specified coordinates through Open-Meteo. Although these screens demonstrate the availability of diverse terrain representations and export controls in the interface, their correspondence with source elevation rasters, field coordinates, and exported file metadata could not be independently verified from the aggregate documentation.



Figure 2. Initial interface of the DEM Data menu in AR-GeoHazard

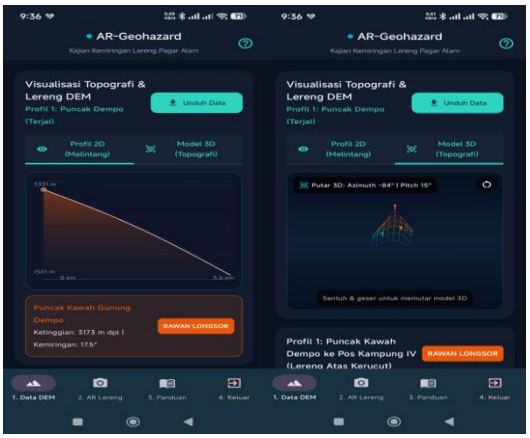


Figure 3. Two-dimensional elevation profile (left) and three-dimensional terrain visualization (right)



Figure 4. Data-export options in the DEM Data menu

The AR Slope interface combines a camera view with a digital pointer, an angular reading in degrees, a percentage-gradient display, and a spirit-level indicator, alongside controls to freeze the display, save an observation, and access previously recorded information (Figure 5). One documented screen displays a slope angle (θ) of 6.0° and a corresponding percentage gradient (g) of 10.5%. Using the trigonometric conversion in Equation (2):

$$g = \tan(\theta) \times 100\% \quad (2)$$

an angle of 6.0° produces a gradient of approximately 10.5104%, which rounds to the displayed value of 10.5%. This example confirms internal numerical consistency between the displayed angle and percentage gradient; however, the presence of these interface components and conversion rules does not establish the physical measurement accuracy of the smartphone sensor across different devices, orientations, or field conditions.

The Guide menu contains operating instructions and explanations of elevation data, slope angles, percentage gradients, and classification categories, as well as mitigation information addressing observable signs of potential ground movement such as ground cracks, tilted trees or utility poles, and slope seepage (Figure 6). Whereas the Exit menu provides a simple confirmation dialog to return to the application or end the session, the classification documentation in the Guide menu maps five technical slope classes into four communication labels (Figure 7). Specifically, flat and gentle slopes share the interface label "Safe," whereas moderately steep, steep, and very steep slopes correspond to "Caution," "Hazardous," and "Critical Danger," respectively (Table 2). While this documentation confirms that the interface consolidates two technical categories into a single communication label, neither user comprehension of the mitigation content nor the exact behavior of the application code at classification boundaries was independently established.



Figure 5. Slope-observation interface in the AR Slope menu

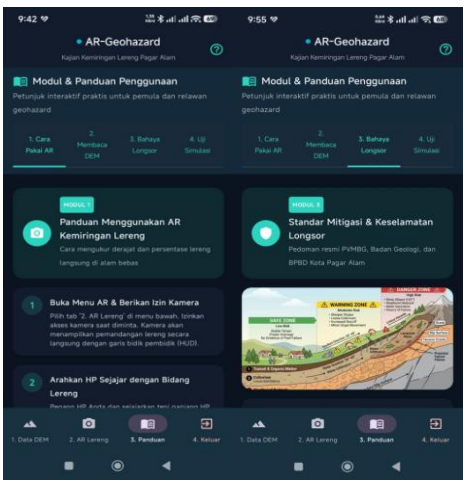


Figure 6. Application operating instructions (left) and mitigation information (right)



Figure 7. Technical slope categories and corresponding communication labels in the Guide menu

Table 2. Technical slope classes and corresponding interface labels

Technical class	Slope gradient	Interface label
Flat	0–8%	Safe (Aman)
Gentle	>8–15%	Safe (Aman)
Moderately steep	>15–25%	Caution (Waspada)
Steep	>25–45%	Hazardous (Rawan)
Very steep	>45%	Critical Danger (Bahaya Kritis)

Overall, the evaluation evidence consisted of interface documentation and aggregate testing summaries across functionality, expert assessment, task completion, perceived usability, and GIS classification agreement (Table 3). Because individual test sheets, expert-response forms, raw user questionnaires, device logs, exported files, and paired spatial-reference records were not included in the aggregate documentation, verification was bounded by the scope of the summarized records.

Table 3. Available evidence and limits of verification

Component	Available evidence	Verification limit
Terrain visualization	Two-dimensional and three-dimensional interface screens	Correspondence with source elevation data was not independently verified
Slope observation	Angle and gradient displays, including the 6.0°/10.5% example	Numerical consistency was checked; sensor accuracy was not established
Recording and export	Save/history controls and export options	Stored records and exported outputs were not independently examined
Guidance and classification	Instructions, mitigation content, and slope-label mapping	User comprehension and classification-boundary behavior were not established
Feasibility evaluation	Aggregate results across five dimensions	Observation-level records were unavailable for independent checking

In the functional evaluation, 38 of the 40 black-box test scenarios passed, yielding an overall functional success rate of 95.00% (Table 4). The DEM Data menu passed 12 of 13 scenarios (92.31%) and the AR Slope menu passed 14 of 15 scenarios (93.33%), whereas the Guide and Exit menus passed all eight and four scenarios, respectively (100.00%). The two recorded failures occurred within the DEM Data and AR Slope menus, although the aggregate testing summaries did not specify their underlying causes or subsequent corrective actions.

Table 4. Black-box testing results across application menus

Menu	Test scenarios	Passed	Failed	Success rate
DEM Data	13	12	1	92.31%
AR Slope	15	14	1	93.33%
Guide	8	8	0	100.00%
Exit	4	4	0	100.00%
Total	40	38	2	95.00%

In the expert evaluation, the two assessors assigned a combined score of 229 out of a maximum of 250 across the five evaluation aspects, equivalent to 91.60% (Table 5). Interface quality as well as navigation and guidance received the highest ratings, each reaching 94.00%, followed by DEM–AR visualization at 92.00% and content and classification at 90.00%. Information safety received the lowest rating at 88.00%, although all assessed aspects exceeded the study-defined feasibility threshold of 80.

Table 5. Expert assessment results

Assessment aspect	Obtained score	Maximum score	Percentage
Interface quality	47	50	94.00%
Content and classification	45	50	90.00%
DEM–AR visualization	46	50	92.00%
Navigation and guidance	47	50	94.00%
Information safety	44	50	88.00%
Total	229	250	91.60%

The user evaluation involved 20 participants attempting five core tasks, resulting in 94 successful completions out of 100 attempts, or an overall task-completion rate of 94.00% (Table 6). Opening a two-dimensional elevation profile achieved a 100.00% completion rate, while reading slope values and locating mitigation guidance each reached 95.00%; in contrast, operating the three-dimensional terrain model and saving an observation yielded the lowest completion rates at 90.00% each. Across the same 20 participants, the composite SUS score reached 1,735, producing a mean perceived usability score of 86.75 on the 0–100 standardized scale. This value exceeded the component threshold of 80, although the absence of item-level questionnaire records precluded an analysis of response variability across individual usability dimensions.

Table 6. Task-completion results for 20 users

Task	Attempts	Successful attempts	Completion rate
Open a two-dimensional elevation profile	20	20	100.00%
Operate the three-dimensional terrain model	20	18	90.00%
Read the slope angle and percentage gradient	20	19	95.00%
Save an observation	20	18	90.00%
Locate mitigation guidance	20	19	95.00%
Total	100	94	94.00%

Finally, the spatial comparison demonstrated agreement between application-generated and GIS-derived slope classes at 28 of the 30 paired reference points (93.33%), with two mismatched locations. Because point coordinates, source rasters, and extraction procedures were not detailed in the summary records, this metric reflects categorical agreement in slope-class assignment rather than smartphone angular precision or landslide-hazard prediction performance. Combining all five evaluation dimensions through Equation (1) produced a weighted feasibility index of 92.19 out of 100, comprising weighted contributions of 23.75 from functionality, 18.32 from expert assessment, 14.10 from task completion, 17.35 from perceived usability, and 18.67 from GIS classification agreement (Table 7). Both the composite index and all five component scores surpassed the threshold of 80, satisfying the study-defined criteria for high feasibility while retaining two unresolved functional failures and two spatial-classification mismatches.

Table 7. Weighted feasibility index for AR-GeoHazard

Evaluation dimension	Score (0–100)	Weight	Weighted contribution
Functionality (F)	95.00	25%	23.75
Expert assessment (P)	91.60	20%	18.32
Task completion (T)	94.00	15%	14.10
Perceived usability (SUS)	86.75	20%	17.35
GIS classification agreement (G)	93.33	20%	18.67
Overall feasibility index	—	100%	92.19

3.2 Discussion

The findings suggest that AR-GeoHazard provides a viable platform for integrating terrain visualization, slope observation, and interpretive guidance within a mobile learning environment. Two-dimensional elevation profiles and three-dimensional terrain models offer complementary representations through which users can explore relationships between elevation changes and landform geometry. This educational potential aligns with Akçayır and Akçayır (2017), who identified learning benefits associated with educational AR alongside usability and implementation challenges, as well as broader systematic reviews highlighting the role of structured digital platforms and computational tools in supporting learning processes (Azevedo *et al*., 2024; Gamage *et al*., 2022; Thwe & Kálmán, 2024). Nevertheless, the present evaluation examined technical feasibility and perceived usability rather than changes in geospatial understanding, knowledge retention, or disaster preparedness. The application's educational contribution should therefore be understood as an opportunity supported by its documented features, with actual learning effectiveness requiring subsequent classroom or field-based assessment. The functional success rate of 95.00%, task-completion rate of 94.00%, and mean SUS score of 86.75 indicate favorable application performance and user perceptions within the evaluated scenarios. Bangor *et al*. (2008) established an empirical basis for interpreting SUS scores as indicators of perceived usability, supporting its inclusion as a core component of the feasibility framework. However, favorable usability ratings do not establish the correctness of terrain data, sensor measurements, or safety-related interpretations. The comparatively lower completion rates for operating the three-dimensional model and saving observations (both at 90.00%) pinpoint specific

interaction workflows that warrant closer attention during interface refinement. Similarly, the two failed functional scenarios in the DEM Data and AR Slope menus require case-level diagnosis because aggregate pass rates cannot reveal their root causes, severity, or practical consequences for end users.

Furthermore, while the numerical consistency between the 6.0° angle and 10.5% gradient verifies the internal trigonometric conversion for that display, and the 93.33% GIS agreement indicates substantial correspondence in categorical slope assignment, these metrics evaluate distinct system properties. Neither finding constitutes proof of smartphone inclinometer accuracy or precise spatial registration between virtual overlays and physical terrain. As emphasized in foundational AR literature (Azuma, 1997), accurate three-dimensional registration remains a primary technical challenge due to inherent sensing and alignment errors. Consequently, AR-GeoHazard's camera-assisted display and terrain models should be evaluated separately for angular measurement error, positional alignment, orientation stability, and fidelity to source elevation models. Resolving the two GIS classification mismatches will likewise require examining point coordinates, raster provenance and spatial resolution, extraction methods, and boundary-rounding rules. The condensation of five technical slope classes into four interface communication labels also raises an important consideration regarding risk communication. Specifically, assigning the label "Safe" to both flat (0–8%) and gentle (>8–15%) slopes may inadvertently encourage users to infer an absence of landslide danger from topographic gradient alone. Studies on data-driven landslide susceptibility modeling consistently emphasize that slope instability arises from complex interactions among multiple geoenvironmental variables rather than gradient in isolation, warning against conflating simple spatial correlations with geomorphic causation (Lima *et al.*, 2021; Steger *et al.*, 2021). Consistent with this concern, information safety received the lowest expert assessment score (88.00%), making the refinement of classification labels a clear priority. A practical revision would display the numerical gradient and technical topographic class while explicitly noting that local slope stability also depends on geology, soil properties, rainfall intensity, drainage, and land use. Finally, although the composite feasibility index of 92.19 satisfied the study-defined "highly feasible" threshold, its interpretation remains contingent on the selected weighting scheme, component cutoffs, and the granularity of the supporting evidence. Because a weighted index aggregates distinct evaluation dimensions, a high composite score can mask localized functional defects or classification discrepancies that require targeted remediation. Moreover, relying on aggregate summaries without observation-level test logs, item-level expert and SUS responses, device hardware specifications, and paired GIS reference files limits independent reproducibility and precludes an analysis of measurement variance. Future work should therefore prioritize resolving the functional failures, revising the safety labels, documenting elevation-data provenance, and conducting repeated multi-device field calibrations, followed by quasi-experimental evaluations of user learning outcomes.

4. Conclusion

This study developed and evaluated AR-GeoHazard, an Android application that integrates elevation profiles, three-dimensional terrain visualization, smartphone-assisted slope observations, recording features, and interpretive guidance for exploring terrain conditions in Pagar Alam, Indonesia. The feasibility evaluation yielded a functional success rate of 95.00%, an expert assessment score of 91.60%, a task-completion rate of 94.00%, a mean System Usability Scale (SUS) score of 86.75, and GIS slope-class agreement of 93.33%. The resulting weighted feasibility index of 92.19 satisfied the study-defined criteria for the "highly feasible" category. These findings support the application's potential as a mobile terrain-visualization and educational tool, although they do not establish smartphone sensor accuracy, spatial registration, improved learning outcomes, or landslide-prediction capability. Further development should resolve the two failed functional scenarios, investigate the two GIS classification mismatches, and refine the three-dimensional navigation and observation-saving workflows. The mapping of five technical slope classes into four interface labels also requires revision, particularly the term "Safe," which may imply greater certainty regarding slope stability than topographic gradient alone can provide. Subsequent evaluations should incorporate traceable elevation-data sources, calibrated field reference measurements, multi-device testing, and complete observation-level records to strengthen reproducibility and independent verification. Finally, direct assessment of users' geospatial comprehension and disaster-preparedness knowledge is needed to establish the application's educational effectiveness in classroom and field settings.

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