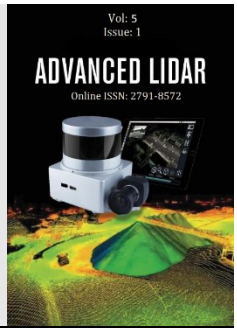
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Research Article /Review Article:

Wearable Mobile LiDAR for Quarry Surveying and Assessment of Geometric and Volumetric Accuracy

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Abstract

Wearable mobile light detection and ranging offers a practical means of measuring quarry floors, benches, slopes and stockpiles, but rapid acquisition does not by itself establish measurement accuracy. This review develops a reproducible framework for evaluating three dimensional geometry and excavation and stockpile volumes using literature published before 2025. A targeted synthesis links trajectory design, independent survey control, point cloud classification, surface representation and uncertainty propagation. The framework separates local surface precision, absolute positional accuracy, repeatability and volumetric agreement. Its analytical assessment shows that a coherent height offset of 0.03 m over a 1000 m^2 footprint produces a volume bias of 30 m^3, irrespective of point count. Occlusion, uncertain base surfaces and inappropriate interpolation can therefore outweigh small local ranging errors. Recommended outputs include spatially distributed checkpoint residuals, signed surface distances, completeness maps and volume sensitivity to base and boundary choices. No quarry observations or instrument benchmark measurements are presented. The contribution is an application specific validation protocol and analytical sensitivity assessment that can guide subsequent controlled field experiments without transferring accuracy claims from unrelated environments.

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Contribution to the field statement:
This review connects quarry measurement deliverables to independent geometric validation and explicit volume uncertainty. It distinguishes observed surfaces from inferred bases and shows why point density and internal registration residuals cannot alone justify a stockpile inventory or excavation estimate.

Highlights:
- Quarry survey quality is linked to the intended measurement task
- Independent checks separate positional accuracy from repeatability
- Base and boundary choices are included in volume uncertainty
- Analytical examples expose the effect of coherent height offsets

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1. Introduction

Quarry operations require reliable descriptions of the terrain and the changing distribution of extracted material. Bench widths, crest and toe positions, haul road gradients and irregular rock faces govern how a site is represented in engineering plans. Stockpile inventories and excavation quantities translate that representation into operational and financial decisions. The same point cloud may support all of these products, yet each product has a different tolerance and a different sensitivity to missing observations. A visually convincing model may therefore remain unsuitable for quantity measurement.

Wearable mobile light detection and ranging (LiDAR) combines laser observations with an estimated sensor trajectory while an operator walks through the site. Its mobility is attractive where repeated tripod setups are inefficient or vehicles cannot enter. In a quarry, however, open floors can offer limited geometric constraints, steep faces can hide benches, and stockpile summits may remain unseen from safe ground. Dust, moving machinery and loose material introduce additional complications. These conditions require acquisition plans based on observability and safe access rather than walking speed alone.

The central problem is the separation of geometric appearance from measurable accuracy. Closely agreeing overlapping strips can share an absolute displacement. A small residual on the points used to fit a transformation does not establish performance at independent locations. Similarly, a repeat survey can reproduce the same incorrect base surface and yield apparently stable volumes. Accuracy assessment must therefore follow the entire chain from control and trajectory estimation to modelling and quantity extraction.

This article examines wearable mobile LiDAR for surveying quarry surfaces, slopes and complex geometries, with particular attention to stockpile and excavation volumes. Its objectives are to organise the relevant evidence, define a reproducible field validation design and derive practical relationships between geometric errors and volume uncertainty. The work is a targeted methodological review with analytical examples. It does not report a new quarry campaign, a site specific accuracy value, or a claim that a particular instrument satisfies a universal tolerance.

2. METHOD

2.1 Review scope and evidence selection

The review considers publications dated no later than 31 December 2024. Twenty five unique records were selected from the supplied reference documents, and ten additional records were selected from the 2022–2024 archive of Advanced LiDAR. Duplicates were removed and records containing the excluded author names were omitted. Selection was purposive: direct relevance to mobile mapping, surface reconstruction, survey validation or volume estimation was required. This is not a systematic review with exhaustive database coverage or a quantitative meta analysis. Bibliographic lists are not equivalent to full texts; where only a supplied citation was available, that record supports the identification of a methodological context rather than a numerical performance claim.

Excavation volume estimation by close range photogrammetry provides an early comparison for deriving quantities from reconstructed surfaces [1]. The relationship between gridding and terrain definition is directly relevant when converting a dense quarry cloud into a digital elevation model [2]. These studies motivate separating acquisition uncertainty from the subsequent numerical representation of the ground; neither provides a transferable accuracy certificate for a wearable system.

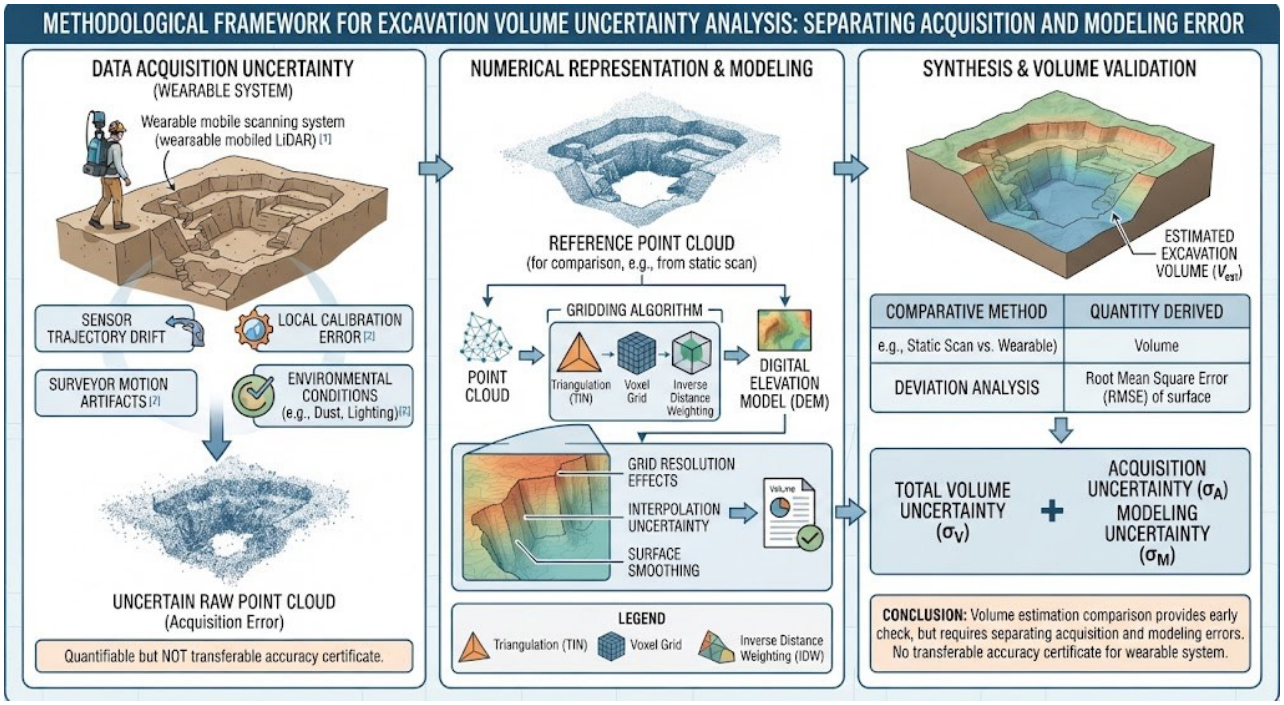


Figure 1: Methodological Framework for Excavation Volume Uncertainty Analysis: Separating Acquisition and Modeling Error.

The mobile mapping component draws on handheld LiDAR and inertial estimation, wide field of view scanning and indoor mobile survey investigations [3, 4, 5]. Published wearable applications at Cambazlı Church and in cadastral mapping, together with a report on incorrect wearable use, define practical contexts for examining route geometry and independent checks [6, 7, 8]. The Mufti Abdullah Sıddık Mosque study provides an additional wearable modelling example [9]. Their environments differ from quarry benches and stockpiles; only the methodological questions are transferred here.

Broader point cloud studies distinguish capture, cleaning, registration and interpretation [10, 11]. Reality capture and multisource modelling reviews also identify acquisition planning and data integration as important parts of a usable geometric record [12, 13, 14]. In this article, those stages are reorganised around quarry deliverables rather than building information models. Figure 1 presents the proposed sequence; its validation stage is independent of the control used during reconstruction.

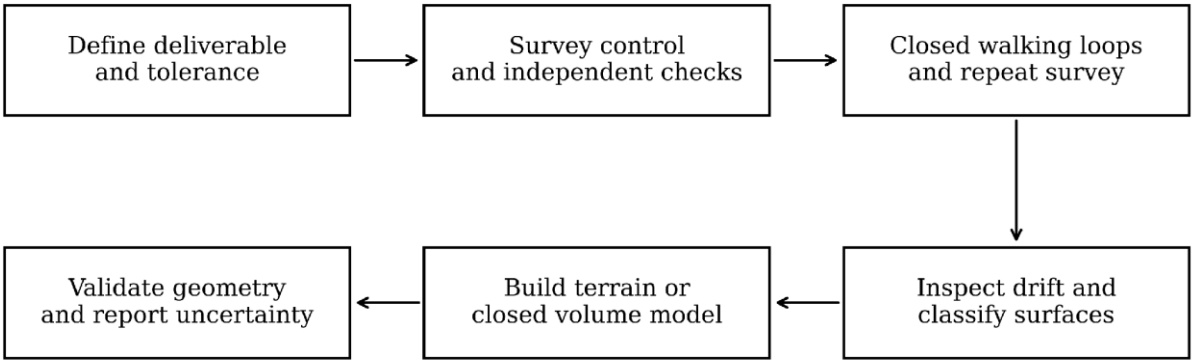


Figure 2. Proposed acquisition and validation workflow for quarry geometry and volume measurement

2.2 Survey design and reference observations

A future validation campaign should sample at least four scene classes: an open quarry floor, a stepped bench system, a steep or irregular face and a stockpile with an independently documented base. A scene with adequate geometric constraints should be paired with a feature poor scene to test trajectory sensitivity. The campaign should document the instrument model, calibration status, firmware, software version, scan settings, time synchronisation, route length, duration, speed variation, loop locations and environmental conditions. These are reporting requirements, not measurements already collected for this review.

Place stable survey control outside excavation and material handling zones. Determine coordinates with an adjusted total station network, differential levelling where necessary, and Global Navigation Satellite System (GNSS) observations where conditions permit. Record the horizontal reference system and height datum, including any geoid transformation. Distribute control in three dimensions so that an alignment is not defined only by nearly collinear targets on one bench. A rigid transformation is preferable when metric scale is physically established; a fitted scale should require an explicit diagnostic justification.

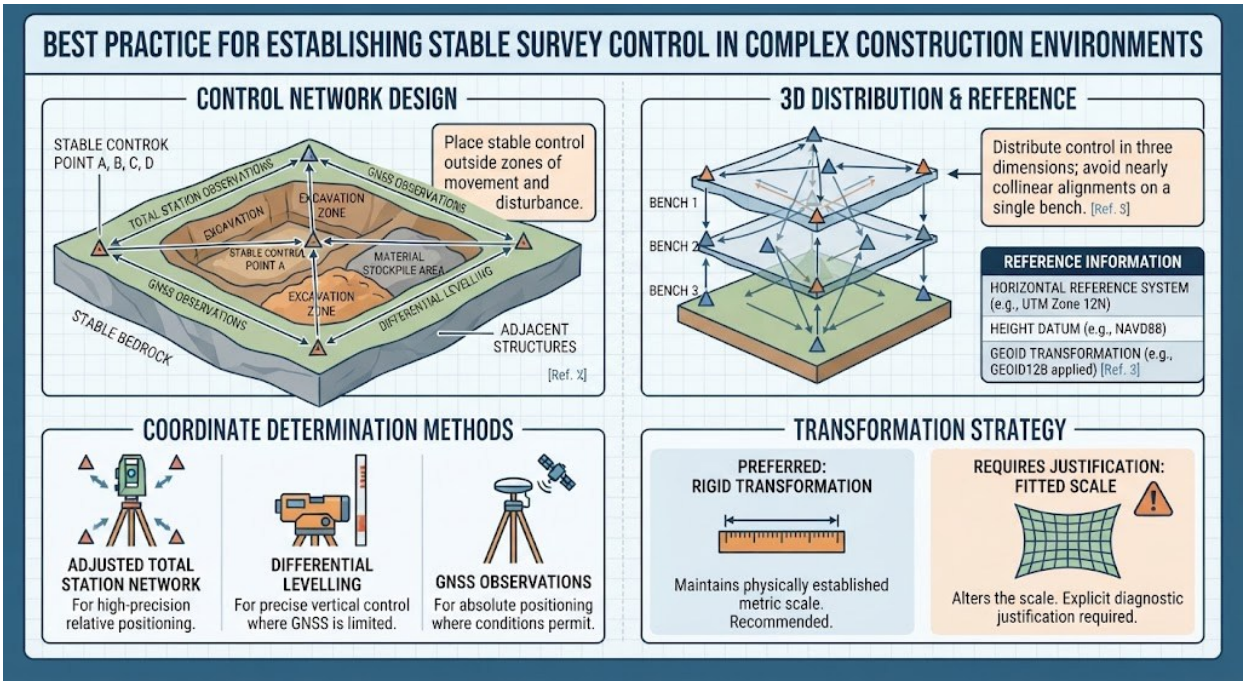


Figure 3: Best Practice Workflow for Establishing Stable Construction Survey Control.

Reserve separate checkpoints and reference patches before processing. They must not participate in trajectory correction, registration or parameter tuning. Place them near the route start, intermediate segments, the furthest excursion, height transitions and the return to the starting area. Report both their number and spatial distribution. A large number of checks clustered around the start cannot diagnose deformation on a distant bench. Reference uncertainty must also be reported and should be sufficiently small relative to the intended product tolerance.

Collect a reference terrestrial laser scanning (TLS) dataset from multiple safe viewpoints where dense geometric validation is needed. Survey the TLS control independently and inspect the reference for its own occlusions and registration errors. Outcrop photogrammetry provides a relevant comparison for difficult access [15], while work on discontinuous urban terrain illustrates why element boundaries deserve explicit representation [16]. Aerial direct georeferencing and UAS topographic mapping studies provide additional examples of platform specific validation designs [17, 18]. Their accuracy values are not adopted as wearable quarry performance.

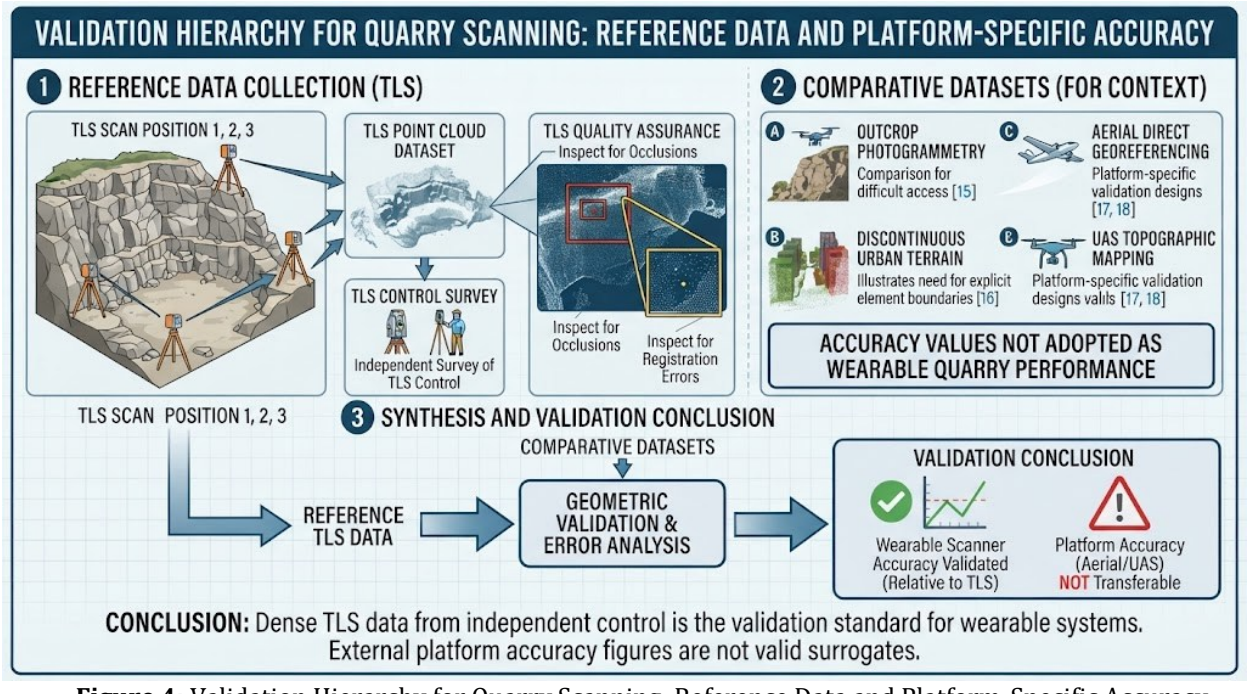


Figure 4: Validation Hierarchy for Quarry Scanning: Reference Data and Platform-Specific Accuracy.

2.3 Acquisition and processing protocol

Plan overlapping walking loops that revisit stable geometry from different directions. Record an independently restarted repeat acquisition, preferably with reversed route direction, to assess repeatability. Crossing a ramp between benches is a critical transition because the local view and elevation change simultaneously. Avoid relying on the final return to correct an extended weakly constrained segment without inspecting intermediate checks. Suspicious double surfaces, abrupt discontinuities and unusually thick planar patches should trigger inspection of the trajectory and raw observations.

During processing, preserve the raw dataset and maintain a reproducible parameter log. Remove transient vehicles, dust returns and isolated noise while retaining sharp crests, toes and small surface discontinuities needed for the deliverable. Perform classification against the intended physical surface. In a stockpile, the pile is the measured material, not a non ground object to be discarded. In a quarry floor model, equipment and vegetation should be excluded but loose rock may belong to the surface if it is part of the operational quantity definition.

Earlier TLS documentation and erosion investigations provide contexts for checking complex and evolving surfaces [19, 20]. The Qobustan petroglyph study demonstrates the application of close range photogrammetry to recording irregular rock surfaces [21]. It is included here as a geometric documentation precedent, not as evidence that wearable scanning reproduces carved detail or achieves a particular quarry accuracy. Stone surface documentation using aerial and combined terrestrial methods likewise motivates retaining local relief and recording material condition [22, 23].

For topographic products, create a triangulated irregular network (TIN) with surveyed or interpreted breaklines where benches and ramps require discontinuities in slope. A raster digital elevation model (DEM) is suitable when the surface is single valued in height at each horizontal position. Overhangs, cavities and near vertical faces require a three dimensional surface representation. Landslide and sea cliff modelling supply related examples of difficult terrain [24, 25]. Independent dimensional comparison is still necessary; an earlier camera based modelling evaluation illustrates why reconstruction capability alone cannot guarantee engineering suitability [26].

Table 1 links each quarry output to an appropriate validation object. The checks are proposed design elements. No count of control targets, scan stations or field observations is implied by the table.

Table 1. Measurement products and independent validation requirements

Product	Representation	Independent validation	Main sensitivity
Quarry floor and ramps	Breakline constrained TIN or DEM	Surveyed heights and cross sections	Datum, filtering and interpolation
Bench and slope geometry	3D cloud, sections and fitted patches	Crest and toe points; local surface normals	Occlusion and alignment
Stockpile inventory	Upper surface plus explicit base	Reference volume with common boundary and base	Base elevation and footprint
Excavation change	Two dated surfaces in one datum	Stable terrain checks and reference sections	Inter epoch alignment and real change

2.4 Positional accuracy and surface completeness

For n independent checkpoints, let ex,i, ey,i and ez,i be the measured minus reference coordinate differences in metres. Equation (1) defines three dimensional root mean square error (RMSE). Report horizontal RMSE and vertical RMSE separately as well; an aggregate value can hide an unacceptable height error. Bias is the componentwise mean residual, and repeatability is evaluated from independent acquisitions rather than by repeatedly reading the same processed cloud.

$$RMSE_{3D} = [n^{-1} \Sigma_{i=1}^{n} (e_{x,i}^2 + e_{y,i}^2 + e_z_{,i}^2)]^{1/2} \quad (1)$$

Evaluate dense surface agreement using signed distances along local reference normals, with a documented normal estimation scale and neighbourhood rule. Closest point distances alone can underestimate lateral displacement on smooth surfaces. Near a vertical face, horizontal displacement contributes strongly to normal distance; on a flat floor, vertical displacement dominates. Report the median, mean, spread and a stated percentile of absolute normal distances for each scene class. Spatially correlated distances must not be treated as millions of independent observations.

A completeness map should distinguish observed surfaces from interpolated or unobserved regions. For a stockpile, explicitly identify whether the crest and back face were observed. For a quarry wall, show shadowed benches and inaccessible recesses. Compute a coverage fraction only against a defined reference support, such as cells on the reference surface that contain valid observations within a declared distance. A percentage without cell size and support definition is not reproducible.

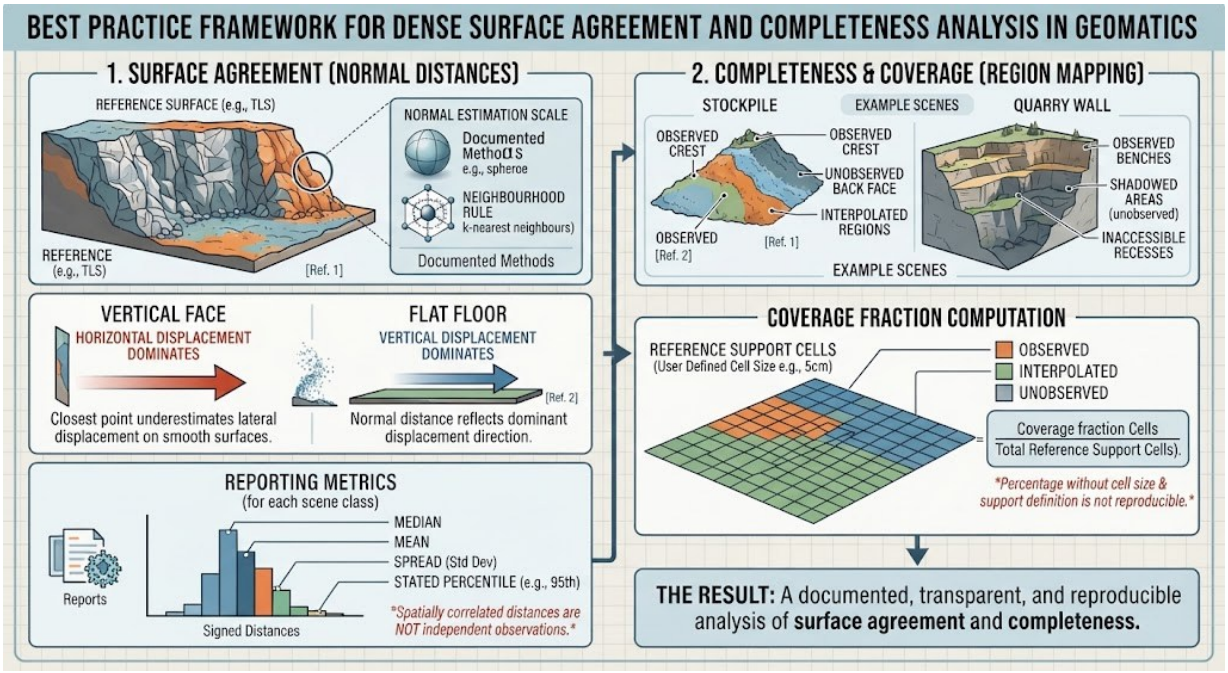


Figure 4: Best Practice Framework for Dense Surface Agreement and Completeness Analysis

2.5 Volume estimation and uncertainty

For a single valued stockpile surface, Equation (2) estimates volume from N cells with horizontal areas Aj. The upper surface zs,j and base zb,j must use the same datum and footprint. Positive and negative differences should be handled according to the task definition; silently clipping negative values can introduce bias. An irregular surveyed base should replace a horizontal base assumption whenever that information is available.

$$V = \Sigma_{j=1}^{N} A_j \, (z_{s,j} - z_b,_j) \quad (2)$$

For excavation change, compute the signed height difference between the later and earlier terrain within a common boundary, and report cut and fill separately. Volume is not material mass: conversion requires bulk density, moisture and compaction assumptions. A change in stockpile shape between survey times is a physical process, not necessarily a sensing error. Surveys intended for platform comparison should therefore be contemporaneous or restricted to demonstrably stable material.

Equation (3) expresses first order propagation for a vector q containing surface heights, base parameters, registration parameters and, where differentiable, boundary coordinates. J is the volume gradient and Σq is their covariance matrix. Correlation terms matter because neighbouring heights may share trajectory drift or a datum offset. If boundary placement or occlusion is strongly nonlinear, use a scenario envelope or a documented simulation instead of presenting linear propagation as exact.

$$u^2(V) \approx J \, \Sigma q \, J^T, \quad J = \partial V / \partial q \quad (3)$$

A spatially coherent vertical offset b between the upper surface and its adopted base produces the bias in Equation (4), where A is the footprint area. If both upper and base surfaces share exactly the same offset, that particular component cancels. Cancellation should be demonstrated, not assumed, especially when the base comes from another survey or an earlier epoch.

$$\Delta V = A \, b \quad (4)$$

A small outward footprint displacement δn(s) changes the volume approximately as Equation (5), where h(s) is material thickness along boundary arc length s. Boundary uncertainty is weak when the pile meets a correctly observed base at zero thickness, but can be important where material is truncated against a wall or where the toe is hidden. Figure 2 illustrates the distinct upper surface and base and the area dependence of coherent bias.

$$\Delta V_boundary \approx \oint h(s) \, \delta n(s) \, ds \quad (5)$$

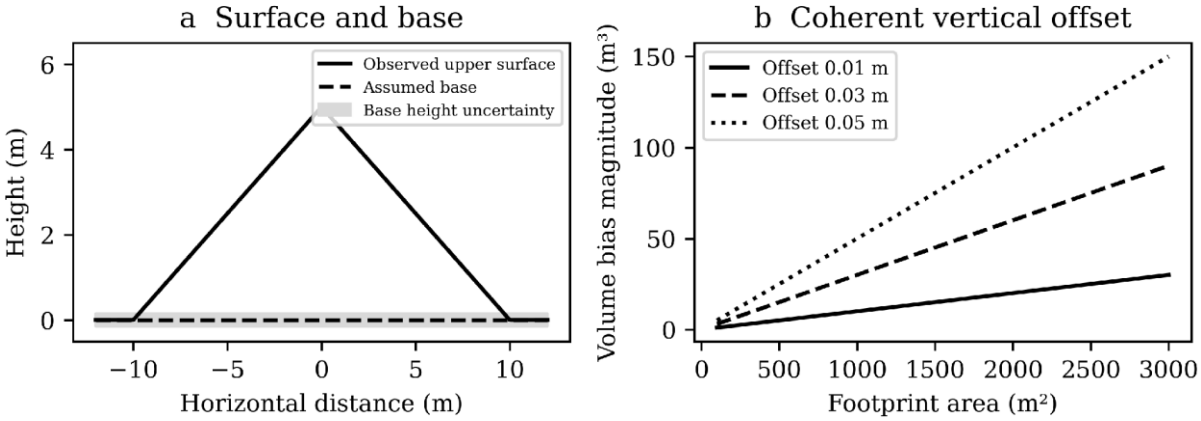


Figure5. Illustrative stockpile cross section and analytical volume sensitivity to a coherent height offset

3 RESULTS

3.1 Evidence synthesis and transfer limits

The result of the review is a validation framework and a set of analytical sensitivities, rather than an empirical ranking of devices. The ten journal studies span wearable building capture, low cost cave reconstruction, terrain filtering, smartphone documentation and TLS based modelling. These are useful methodological comparisons but do not constitute ten independent quarry validation experiments. Table 2 separates the transferable question from the unsupported extrapolation.

The cave modelling study explicitly discusses profile gaps and sidewall overlaps [27]. Its relevance is the treatment of incomplete geometry, not a wearable stockpile accuracy value. The Skopje analysis compares terrain volumes under different filtering settings and finds that manual refinement remains important [28]. The smartphone necropolis comparison and the archaeological excavation comparison examine complementary reconstruction approaches [29, 30]. Their sensor types and object scales must remain visible when interpreting the evidence.

The Farabi Mosque study evaluates processing in multiple software packages, including area, mesh and volume operations [31]. The Sarı İsmail Sultan Tomb study describes TLS based geometric documentation [32]. Airborne ground filtering studies emphasise sensitivity to scene characteristics and chosen parameters [33, 34]. The Şanlıurfa Kışla Mosque paper supplies a further example of stone surface documentation [35]. In quarry work, these contexts support processing checks and careful surface interpretation; they do not justify importing a setting or tolerance unchanged.

Table 2. Transferable lessons from the ten Advanced LiDAR records

Evidence group	Records	Transferable question	Limit of transfer
Wearable building capture	Mufti Abdullah Sıddık Mosque	Can control and route geometry support a usable model?	Building scenes differ from open quarry floors
Terrain filtering	Skopje and two CSF studies	How do parameters alter terrain and integrated volume?	Airborne filters may remove the stockpile itself
Alternative capture	Cave, smartphone and excavation studies	Which surfaces are actually observed?	Sensor geometry and object scale differ
TLS and stone documentation	Farabi, Sarı İsmail and Kışla studies	How are registration, modelling and local relief checked?	Architectural documentation is not quarry validation

3.2 Analytical sensitivity of quarry volumes

Equation (4) yields the exact results in Table 3 for the stated coherent offsets. The values are synthetic calculations and are not observations, instrument specifications or published field results. For an illustrative 1000 m^2 stockpile with a true volume of 5000 m^3, a differential offset of 0.03 m produces 30 m^3 bias, or 0.6%. Increasing point density does not reduce this coherent component. For an excavation quantity of only 500 m^3 over the same

footprint, the same bias becomes 6%. The consequence depends on the quantity being measured, not on footprint area alone.

Table 3. Calculated volume bias from assumed coherent vertical offsets

Footprint area m^2	Offset 0.01 m	Offset 0.03 m	Offset 0.05 m
100	1 m^3	3 m^3	5 m^3
500	5 m^3	15 m^3	25 m^3
1000	10 m^3	30 m^3	50 m^3
2500	25 m^3	75 m^3	125 m^3

For comparison, assume 1000 cells of 1 m^2 and a per cell independent random height standard uncertainty of 0.03 m, with a perfectly known base. Equation (3) then gives $u(V) = 0.03\sqrt{1000} = 0.95$ m^3. If the same 0.03 m uncertainty instead represents one fully correlated offset across all cells, $u(V) = 30$ m^3. Both examples use the same marginal height uncertainty, but their volume uncertainties differ by approximately a factor of 32. Real clouds generally contain a mixture of short and long range correlation; neither limiting case should be adopted without justification.

Occlusion produces a different problem. If an unseen region has area 100 m^2 and two plausible reconstructions differ by an average height of 0.20 m, their estimated volumes differ by 20 m^3. This is a scenario difference, not a measured error or a probabilistic confidence interval. It should be reported as model sensitivity until independent observations constrain the missing surface. Base selection should be tested in the same manner by comparing a surveyed base, a justified fitted base and any operationally used simplified base.

3.3 Deliverable based acceptance logic

A candidate dataset is acceptable only after the intended task and tolerance are defined. Geometry, completeness and volume checks are complementary gates. A dataset can pass a checkpoint test and still fail stockpile completeness, or reproduce a total volume while misplacing a bench crest. Table 4 states the proposed decisions without assigning arbitrary centimetre thresholds. Thresholds should come from the engineering specification and the uncertainty of the independent reference.

Table 4. Proposed acceptance gates for future quarry campaigns

Gate	Required evidence	Decision when evidence is inadequate
Reference integrity	Survey adjustment, datum and independent reference uncertainty	Improve reference before judging the wearable dataset
Positional accuracy	Distributed checkpoint residuals and bias by scene class	Reprocess or reacquire affected routes
Surface completeness	Coverage map and observed or inferred status	Add viewpoints or report an explicit model envelope
Volume robustness	Common base and boundary; sensitivity and uncertainty budget	Withhold inventory grade claim for the affected quantity
Reproducibility	Independent repeat route and retained processing settings	Limit conclusions to the documented acquisition

4 DISCUSSION

4.1 Why local precision does not establish inventory accuracy

The analytical examples reveal that a quarry quantity inherits errors at several scales. Instrument ranging noise acts locally, while trajectory drift can deform a large region and base uncertainty can affect an entire stockpile. Reporting only a surface fit residual obscures this distinction. A best fit alignment against the same reference used for evaluation can also absorb displacement and rotation, producing optimistic residuals. For a valid comparison, the transformation should be estimated from designated control, frozen, and then assessed at withheld checks.

The acquisition and processing distinctions in the broader point cloud literature [10, 11, 12] support this separation, but the quarry interpretation developed here is task specific. A bench survey needs credible crest and

toe geometry. An inventory needs a closed quantity definition and a defensible base. A change survey needs stable reference terrain and coordinated acquisition times. Combining these objectives into one overall accuracy number weakens rather than strengthens the evidence.

The reference itself requires scrutiny. Even a dense TLS cloud has missing regions and uncertain registration. Differences between two sensors are agreement statistics until the reference uncertainty is characterised. Where independent uncertainties are justified, their covariance can be propagated into the comparison. Where both datasets share control or processing constraints, the resulting dependence must be retained. Repeated acquisition is useful, but repeated agreement alone cannot identify a common systematic bias.

4.2 Complex geometry and multisensor completion

Wearable acquisition is most promising when safe walking routes provide changing views and enough stable geometry for trajectory estimation. It is less informative when the operator sees only the toe of a large pile or a feature poor floor for a long distance. In those cases, a complementary TLS viewpoint, aerial survey or targeted total station section can address a specific missing part. Integration should be justified by the gap it closes and validated in the shared reference system, following the general multisource perspective of the reviewed studies [14, 13].

A two dimensional height model cannot represent an overhang because more than one height exists at the same horizontal location. Filling such a cloud into a DEM may create fictitious material. A closed three dimensional mesh can represent this geometry, but its volume depends on closure faces, topology and outward normal consistency. The analyst should show which faces are observed, which are interpolated and which close the model against an assumed base. A watertight mesh is a computational condition, not proof of physical completeness.

The Qobustan study [21] is relevant to preserving irregular rock form and recording detail, while the erosion and difficult terrain studies [20, 24, 25] relate to evolving natural geometry. Their inclusion should remain proportionate: small carved surfaces, earth pillars and coastal cliffs are not operational quarry stockpiles. They help frame geometric questions but do not supply missing quarry experiments. Similarly, the cadastral wearable study [7] demonstrates a different validation setting, not an assurance that the same accuracy survives on an open bench.

4.3 Limits and priorities for experimental validation

The evidence set is constrained by the supplied bibliographies and the requested journal allocation. It contains conference papers and non quarry applications alongside journal studies. It should not be used to estimate a pooled wearable accuracy or to claim comprehensive coverage of the field. Citation counts were unavailable for the specified Google Scholar profile and were not inferred from Crossref, Scopus or publisher counts. Those services measure different citation sets and cannot silently substitute for the requested filter.

Future experiments should compare repeat routes with different loop structures while holding the reference network, scene and processing decisions constant. Report route dependent drift at withheld checks before and after any correction. Compare volumes with a common base and footprint before exploring alternative modelling choices. This order isolates acquisition effects first and modelling effects second. Additional tests should quantify the influence of stockpile size, bench spacing, missing crest observations, dust and moving equipment on usable coverage and quantity uncertainty.

A useful publication should make the final quantity traceable to raw observations, processing settings and explicit assumptions. Minimum reporting comprises sensor and software versions, coordinate and height systems, acquisition times, control and check roles, reference uncertainty, route geometry, filtering settings, surface resolution, base provenance, footprint definition and all interpolation or mesh closure decisions. This protocol is more informative for transfer to another quarry than a single favourable RMSE. Field evidence is still required to establish the achievable accuracy and efficiency of any particular system.

5 CONCLUSION

Wearable mobile LiDAR offers a practical platform for acquiring three dimensional quarry geometry, but its suitability must be evaluated against the intended product. Bench and slope surveys require independent positional and surface checks; stockpile and excavation quantities additionally require explicit bases, boundaries and completeness assessments. Internal alignment residuals and point density do not establish those conditions.

The proposed framework separates local surface precision, absolute accuracy, repeatability and volume uncertainty. Analytical examples show that a 0.03 m differential height offset over 1000 m^2 produces 30 m^3 of volume bias and that correlation can dominate the integrated uncertainty. Missing surfaces and uncertain bases should be reported through justified sensitivity scenarios rather than concealed by interpolation.

This article provides a reproducible methodological basis for a subsequent controlled quarry campaign. It does not establish a measured accuracy, an instrument ranking or a universal operational tolerance. The next step is an independent field comparison across open floors, benches, steep faces and stockpiles, using declared acceptance limits and a reference whose uncertainty is documented.

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Conflicts of Interest

The author must confirm his financial, professional and editorial relationships before submission. No conflict declaration is inferred in this draft.

Data Availability Statement

No new quarry measurements were collected for this review. The analytical examples are fully specified in Equations (2)–(5) and Table 3. The supplied reference documents and publicly accessible publication records form the evidence basis.

Institutional Review Board Statement

Not applicable. This review includes no human participants, personal research data or animal experiments.

CRediT Author Statement

Atila Karabacak is the sole author. The CRediT roles and responsibility for the final manuscript must be confirmed by the author before submission.

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