A multi-methodological workflow for fractured rock slope stability and block volume estimation

Foletti M.G.[1], Menegoni N.[1], Poggi E.[2], Benedetti G.[2], Comedini M.[2], Elmo D.[3], Maino M.[1]

1. Department of Earth and Environment Sciences, University of Pavia; 2. Gruppo FS Engineering SpA, Gruppo Ferrovie dello Stato Italiane; 3. NBK Institute of Mining Engineering, University of British Columbia, Vancouver, CO, Canada.

1. Introduction

Accurate estimation of **discontinuity intensity** and **rock block volume** (***Vb***) is a fundamental requirement for assessing rockfall hazards and the mechanical behavior of rock masses. The primary challenge in this field is overcoming the inherited biases of traditional surveys and qualitative indices (e.g., ***RQD***, ***GSI***) by integrating multi-scale data, from macro-structures to centimeter-scale fracture networks.

In response to these needs, this study proposes a multi-scale, integrated workflow that combines 3D structural mapping from **Digital Outcrop Models** (***DOMs***) with **high-resolution 2D image analysis**. By processing these multi-source datasets, a robust In-Situ Block Size Distribution (***IBSD***) was generated and directly compared with the Rockfall Block Size Distribution (***RBSD***) measured from actual deposits.

This quantitative approach enables a **robust**, **data-driven** and **reproducible** transition from a qualitative rock mass parametrization to high-fidelity geoengineering assessment.

2. Case study

Located in **Molassana** (**Genoa**, **Italy**), the study area features the **Monte Antola Formation**.

The site consists of a complexly folded, well-bedded marly-limestone flysch (layers up to 80 cm -1m) interbedded with thin argillaceous shale levels (up to 30 cm).

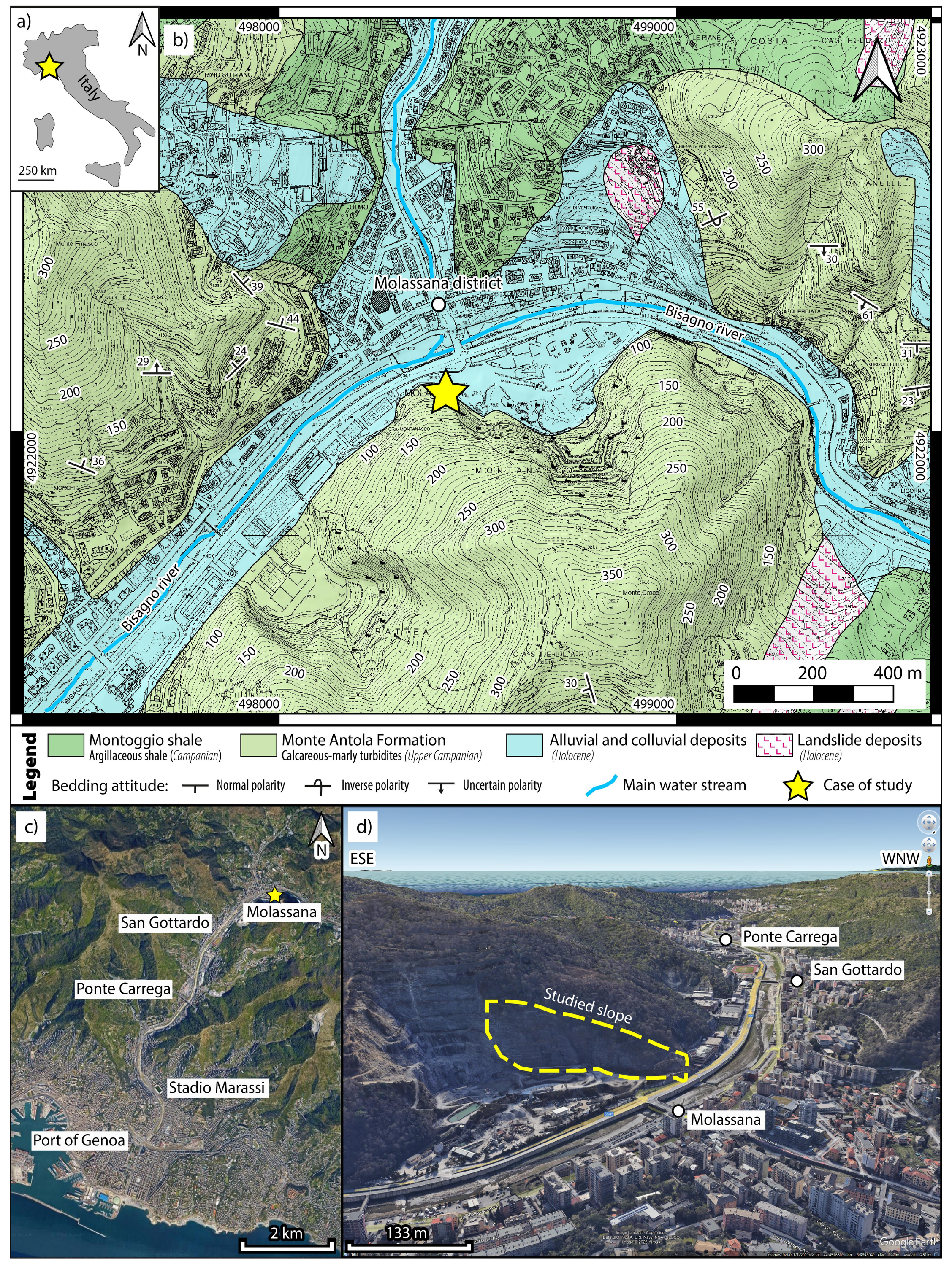

Fig. 1. (a) Geographical and (b) Geological setting of the study area; (c) Orthophoto of the city of Genoa; (d) South-east view of the study area.

3. Methodology

The process is organized into a series of sequential operational stages:

(1) Input data acquisition

(2) Discontinuity network, spacing and discontinuity intensity analysis

(3) In-Situ Block Size Distribution (***IBSD***) estimation

(4) Output generation (***CDFs*** and ***CDVs***)

(5) Validation through Rockfall Block Size Distribution (***RBSD***) comparison

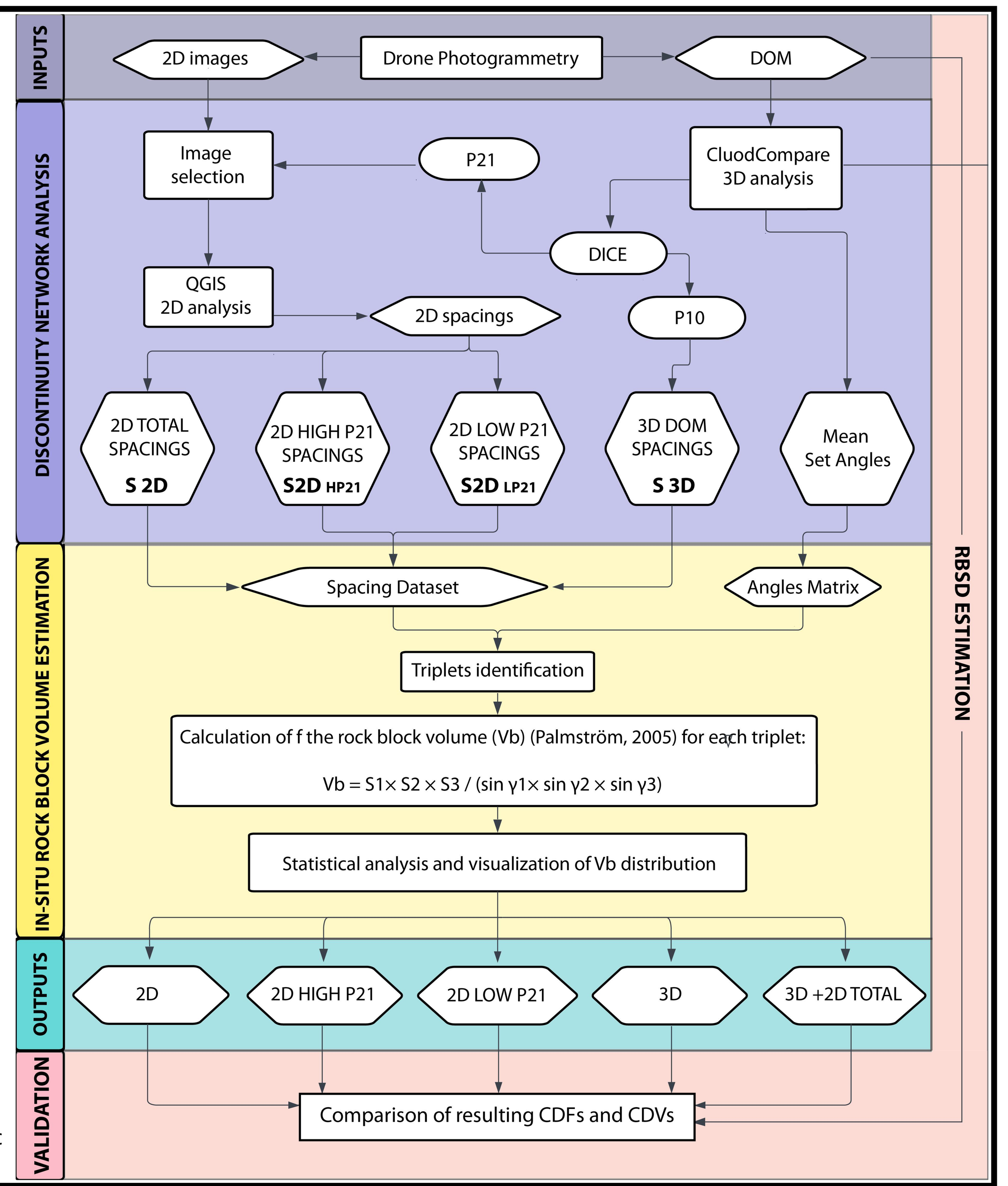

Fig. 2. Methodological flowchart of the integrated 2D-3D approach for probabilistic block volume (*Vb*) estimation.

4. Discontinuity network analysis

Table 1. Acquisition and Mapping Resolution Thresholds (2D vs 3D)

	2D Approach (UAV images)	3D Approach (DOM)
Nominal Resolution (NR)	1.03 cm/pixel	2.06 cm (point spacing)
Mapping resolution (2-3 x NR)	2 - 3 cm	3 - 6 cm
Min. mapped discontinuity size	3 cm	10 cm
Min. mapped spacing size	3 cm	11 cm

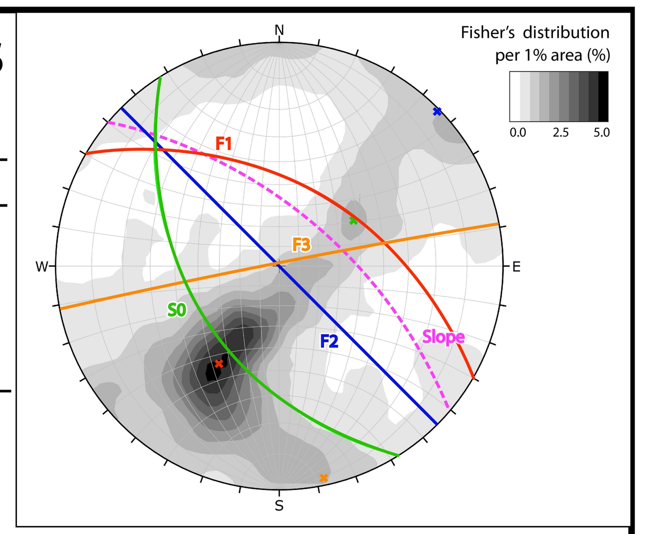

Fig. 3. Stereonet showing the orientations of the identified sets.

INPUT DATASET

- **3041 3D discontinuities** were mapped on the DOM ($16{,}000\ m^2$).
- **3079 2D discontinuities** were mapped on high-resolution UAV images within six Scan Windows ($12\ m^2$ each).
- **Four main sets** were identified: S0 (47/238), F1 (51/029), F2 (89/224), and F3 (87/349).

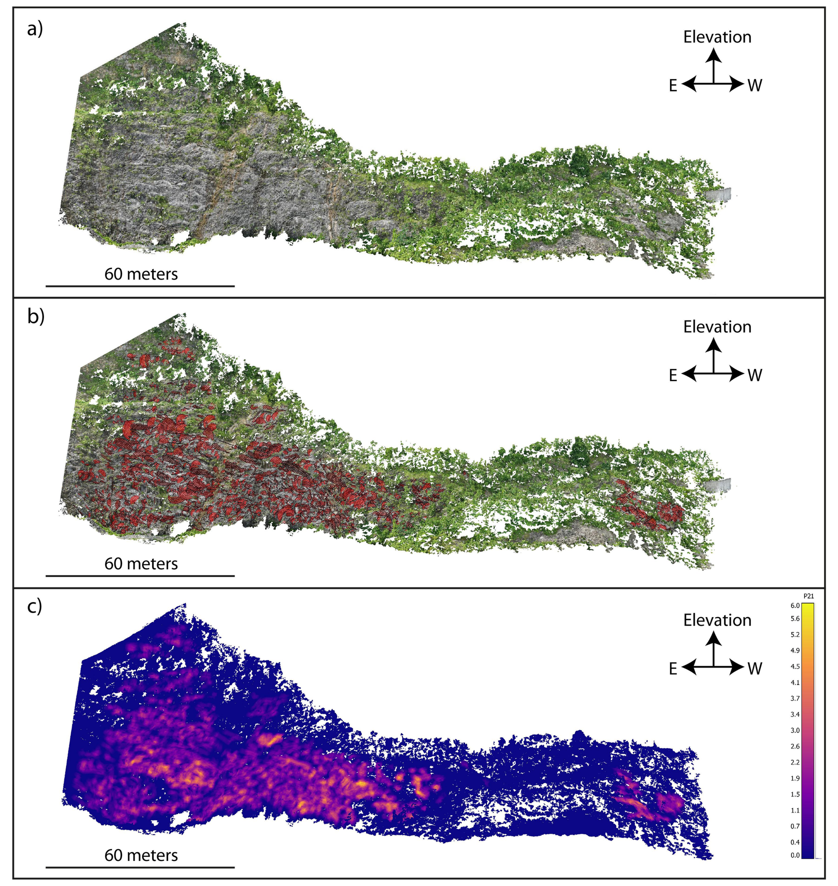

Fig. 4. (a) DOM representing the studied rock cliff, (b) 3D mapped discontinuity network represented using the Baecher's disk model and (c) areal discontinuity intensity (P21) estimated by DICE.

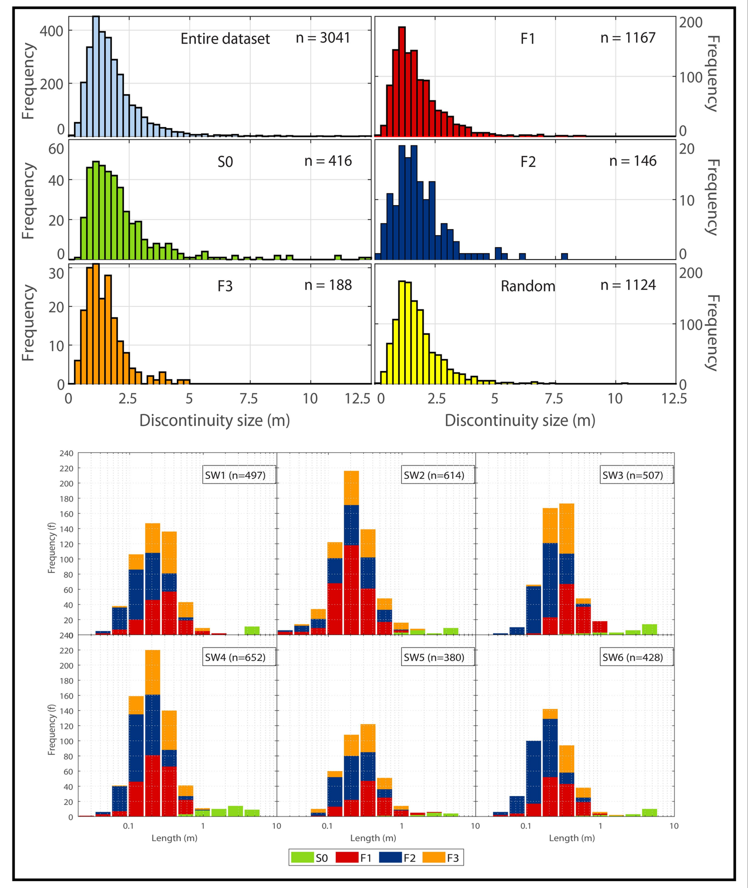

Fig. 5. Dimensional characterization of discontinuities: 3D (above) and 2D (below)

5. Discontinuity intensity and spacing

3D Analysis:

P10, P21 and spacing are calculated on DOM with DICE algorithm.

2D Scan-Windows (SW) selection:

2D SWs were selected based on the 3D P21 distribution values. Three representing high intensity (**HP21**) and three low intensity (**LP21**).

2D Analysis:

traces and spacing are mapped on UAV images within the selected windows.

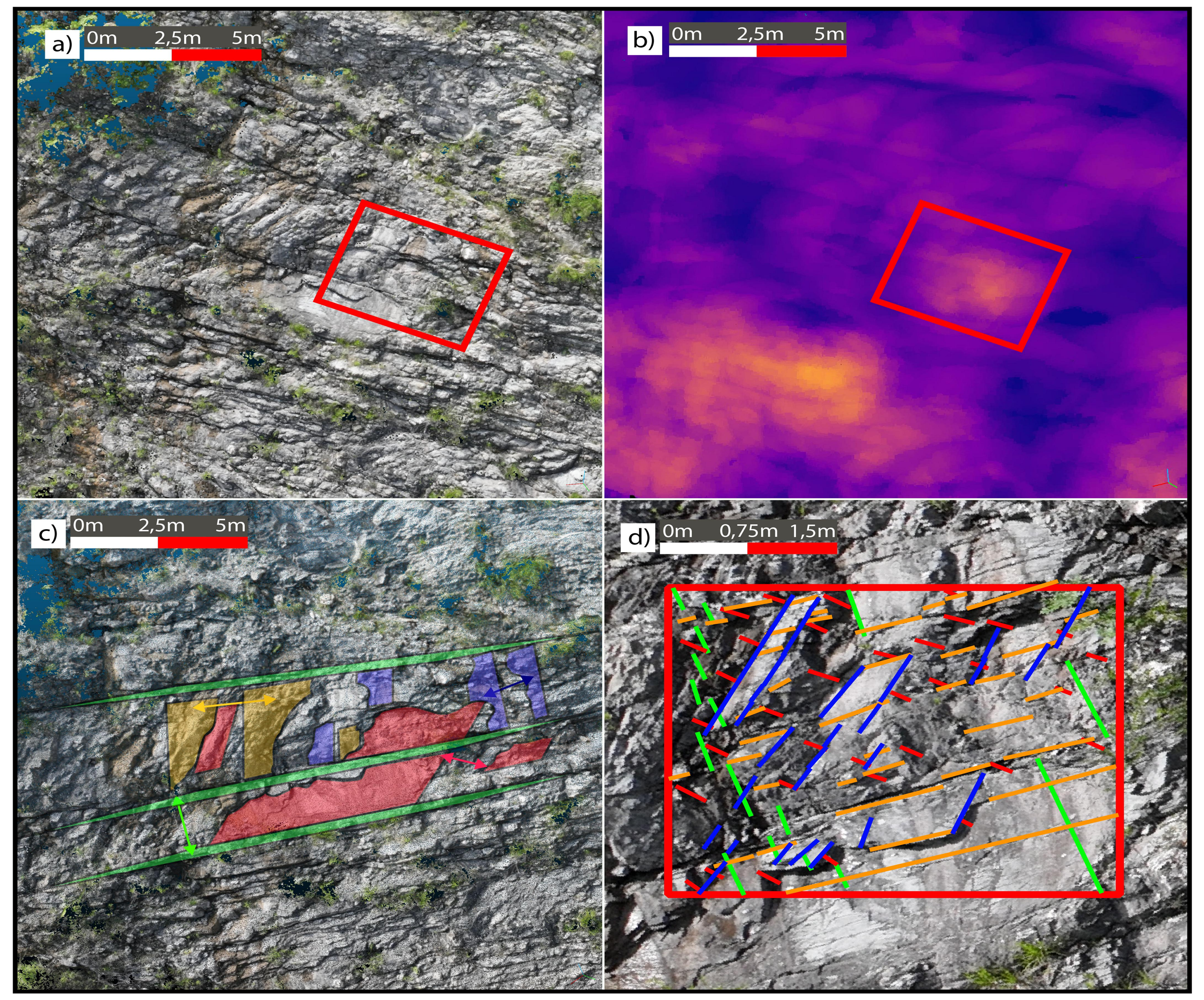

Fig. 6. (a) 3D map of the study area; (b) Scan Windows (SW) positioned on the P21intensity map for multi-scale analysis; (c) Example of 3D plane fitting; (d) 2D fracture mapping in QGIS within a Scan Window, showing 2D spacing distribution categorized by discontinuity sets.

6. Rock block volume estimation

IBSD ESTIMATION

Table 2. Spacing data per discontinuity set across the 2D and 3D datasets.

Discontinuity Set	Number of spacing measures: S 3D	S 2D (HP21)	S2D (LP21)	S2D	S 2D+3D
S0	66	136	48	184	250
F1	106	219	90	309	415
F2	11	212	98	310	321
F3	9	211	108	319	328

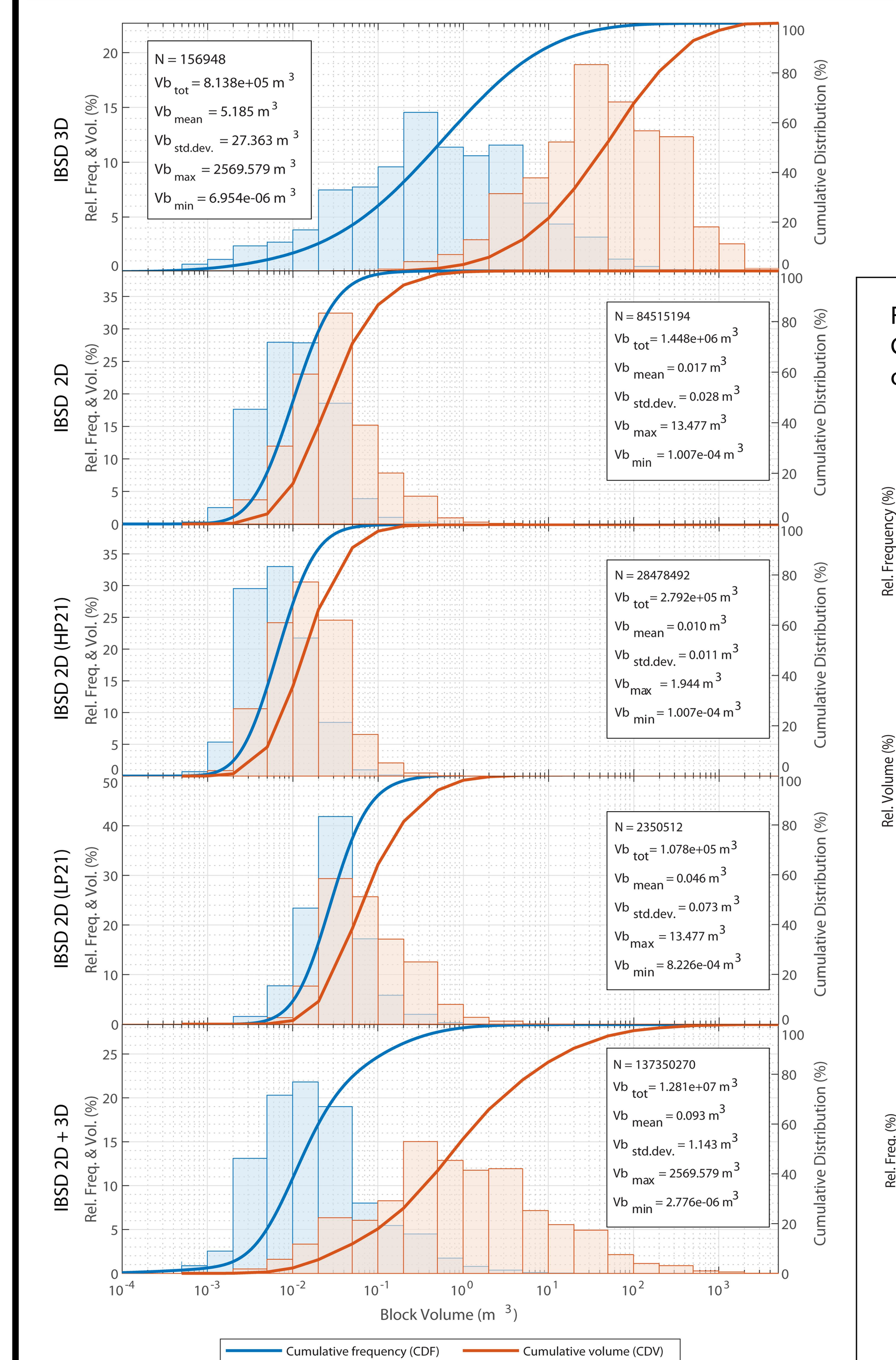

Fig. 7. Cumulative Distribution Function (CDF) and Cumulative Distribution of Volumes (CDV) curves obtained from the various spacing datasets derived from 3D and 2D outcrop analyses.

RBSD CALCULATION

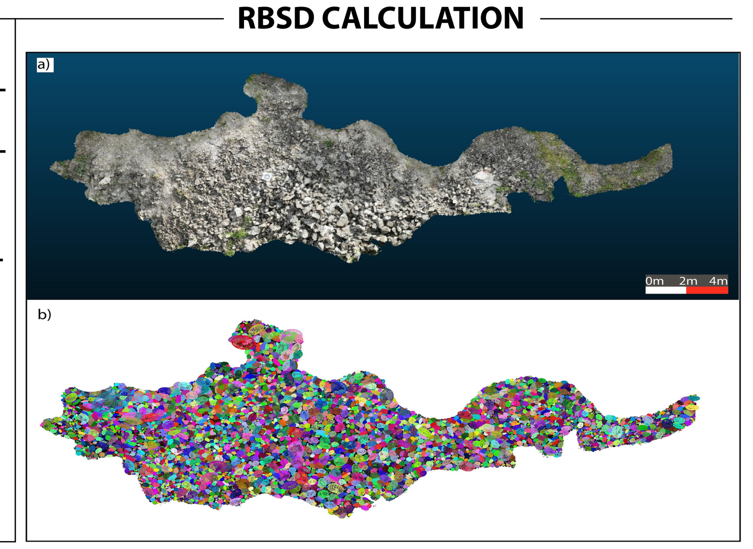

Fig. 8. Model of the deposit at the base of the outcrop, used for G3Point fitting analysis; (b) Result of the ellipsoidal fitting performed on the 3D model.

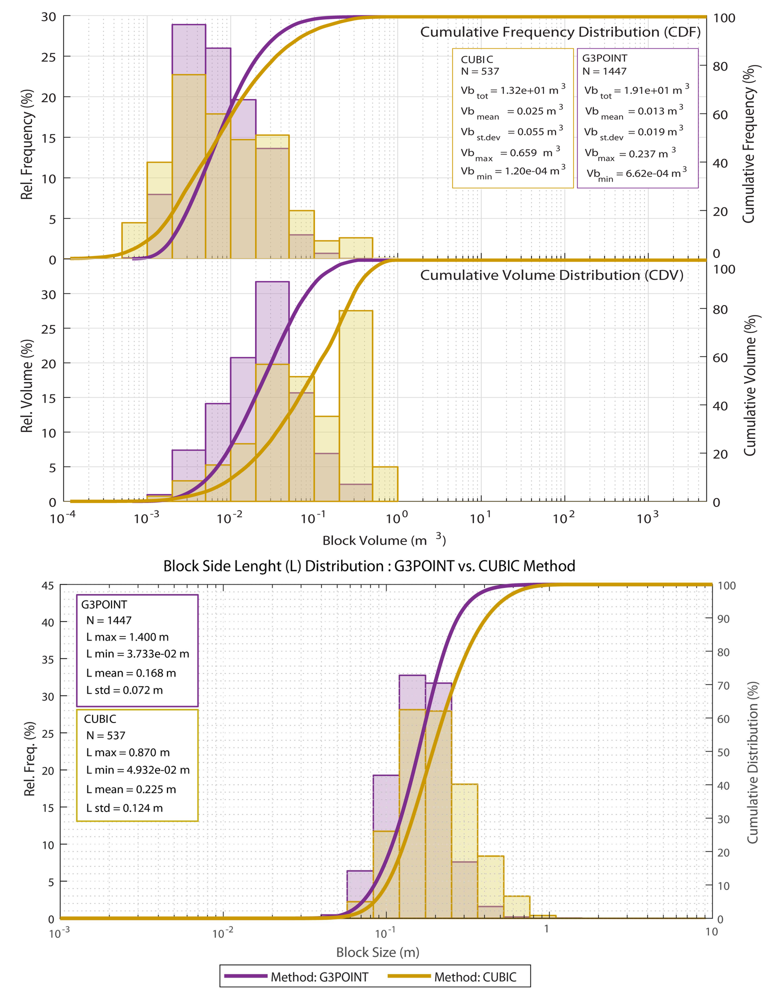

Fig. 9. Block volume distributions (Vb) (above) and Rockfall Block Side Length (L) (below) distributions comparisons between the Cubic Method and G3Point analysis.

7. Discussion

Multiscale Volumes: Vmean drops from $5.19\ m^3$ (3D-only) to $0.02\ m^3$ (2D-only), reaching a realistic $0.09\ m^3$ through 2D+3D analysis.

Validation: Digital IBSD models are validated by physical RBSD debris analysis, showing the highest affinity with high-resolution 2D mapping results.

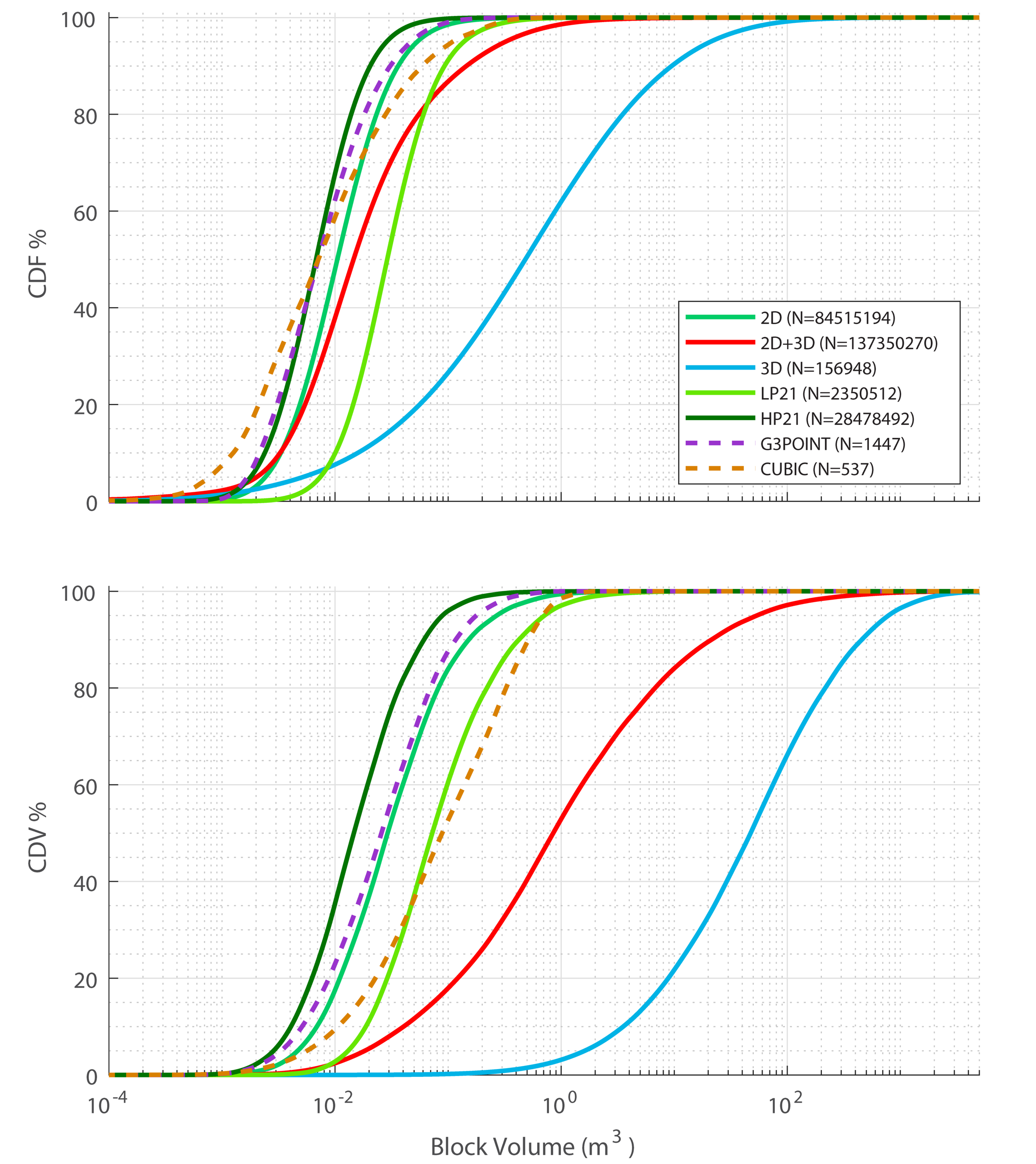

Fig. 10. Cumulative Distribution Function (CDF) and Cumulative Volumetric Distribution (CDV) curves obtained from IBSD and RBSD analysis.

Table 3. Comparison of Block Volumes and Equivalent Lengths (Leq) across IBSD and RBSD datasets

Volume Dataset	Vmin [m^3]	Min Leq [m]	Vmean [m^3]	Mean Leq [m]	Vmax (99.9% CDF) [m^3]	Max Leq [m]
IBSD 3D	7×10^{-6}	0.02	5.19	1.73	394.00	7.33
IBSD 2D	1×10^{-4}	0.05	0.02	0.25	0.42	0.75
IBSD 2D HP21	1×10^{-4}	0.05	0.01	0.21	0.10	0.46
IBSD 2D LP21	8×10^{-4}	0.09	0.05	0.35	0.94	0.98
IBSD 2D + 3D	3×10^{-6}	0.02	0.09	0.45	9.22	2.10
RBSD Cubic	1.2×10^{-4}	0.05	0.03	0.29	0.51	0.80
RBSD G3Point	6.6×10^{-4}	0.09	0.01	0.23	0.25	0.63

8. Conclusions

Scale and Methodology Dependency Biases: 3D mapping tends to overestimate volumes; 2D captures essential centimetric fractures.

Methodological Innovation: from subjective manual surveys to standardized digital workflows.

Validation through RBSD: Calculated IBSD matches RBSD measurements.

Optimization of Geo-engineering: realistic protection design based on actual fragmentation.