

Evaluation of proxies of the averaged shear-wave velocity to a depth of 30 m (V_{s30}) for site characterisation in Italy

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ABSTRACT Near-surface geological conditions strongly influence seismic ground motion, and the time-averaged shear-wave velocity to a depth of 30 m (V_{s30}) is a commonly used parameter to describe site effects in ground-motion models applied in shaking scenarios and seismic hazard assessment. However, the limited availability of direct V_s measurements has led to the growing use of morphometric and geological proxies. This study examines the relationship between V_{s30} and a comprehensive set of topographic and lithological proxies across Italy, utilising a dataset comprising approximately 15,000 V_s profiles distributed across Italy compiled from seismic microzonation studies, regional databases, and the Italian ACcelerometric Archive (ITACA). Topographic proxies were derived from the high-resolution (10 m) national digital terrain model, resampled to multiple spatial scales (150–1000 m), while lithological information was obtained from the national maps and complemented by global soil thickness data. This study provides the first nationwide assessment of multi-proxy correlations with V_{s30} in Italy and establishes the foundation for the development of a robust, spatially continuous, and lithologically informed V_{s30} model.

Key words: V_{s30} dataset, topographic proxies, correlation analysis, lithological classification.

1. Introduction

Numerous earthquakes have demonstrated that near-surface geological conditions can significantly impact both the amplitude and the spatial distribution of shaking and damage. Well-known examples include the 1985 M_w 8.1 Michoacán earthquake (Singh and Ordaz, 1993), the 1989 M_w 6.9 Loma Prieta event (Hough *et al.*, 1990), and the 1994 M_w 6.7 Northridge earthquake (Spudich *et al.*, 1996), all of which highlighted the role of local site amplification. These cases confirm that, alongside source and path effects, site effects are a fundamental factor in shaping ground-motion intensities (Aki, 1988; Boore *et al.*, 1997; Field, 2000).

The use of V_{s30} , defined as the time-averaged shear-wave velocity to a depth of 30 m, was formally introduced by Borcherdt and Glassmoyer (1995) to unambiguously describe site classes and coefficients for the 1994 United States National Earthquake Hazards Reduction Program (NEHRP) (Martin and Dobry, 1994), and was subsequently adopted worldwide. Its popularity stems from the fact that it is a simple metric that can be obtained by means of noninvasive surface-wave methods (Yong *et al.*, 2016).

Nowadays, V_{s30} is commonly used to account for site effects in empirical ground-motion models (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008;

Chiou and Youngs, 2014; Lanzano *et al.*, 2019), for the identification of soil categories in seismic codes (CEN, 2004; MIT, 2018) and to derive seismic risk maps.

However, despite its widespread use, several studies have pointed out that V_{s30} does not fully capture the complexity of local seismic response, especially in the presence of strong velocity impedance contrasts and in deep sedimentary basins (Lee and Trifunac, 2010; Paolucci *et al.*, 2021). These limitations have encouraged a gradual shift towards multi-parameter site-characterisation frameworks. In Italy, the updated seismic code NTC 2018 (MIT, 2018) introduces equivalent shear-wave velocity as an alternative to V_{s30} , incorporating the depth to the engineering bedrock, defined by a shear-wave velocity of 800 m/s. Similarly, Pitilakis *et al.* (2018) and other authors note that V_{s30} is not always the most appropriate descriptor of site amplification under all conditions, and that complementary parameters such as deposit thickness and site fundamental frequency or period should also be considered. Nevertheless, V_{s30} still remains the most used proxy of seismic site amplification. However, the cost and logistical effort of geophysical tests to measure the shear-wave velocity profile prevent the systematic application across large areas. This limitation has motivated the development of alternative approaches to retrieve V_{s30} based on proxies, which enable cost-effective and spatially continuous estimates of this parameter.

In this perspective, the present study provides an initial step towards assessing which large-scale, spatially continuous proxies may contribute to more comprehensive and operational site-characterisation approaches in Italy.

Among these, topographic slope has become one of the most widely used proxies due to the global availability of digital elevation models (DEMs). Wald and Allen (2007) first proposed slope alone as a global proxy for V_{s30} , relying on the empirical observation that stiffer materials tend to sustain steeper slopes, whereas softer sediments commonly occur in flatter terrains. While conceptually simple and computationally efficient, slope-only models often introduce regional biases (Yong *et al.*, 2012). To overcome these limitations, subsequent studies combined slope with additional geological information. For instance, Thompson *et al.* (2014) and Wills *et al.* (2015) integrated slope with surface geology in California, significantly improving predictive performance and reducing regional biases.

Other works have emphasised the role of the depositional setting, noting that environments such as alluvial fans, lacustrine basins, or colluvial deposits exhibit distinct velocity patterns even when slopes are similar (Yong *et al.*, 2012; Parker *et al.*, 2017; Choi *et al.*, 2025). Additional improvements come from including sediment thickness and basin structure, which control the depth to bedrock and the impedance contrast at shallow depths, thereby influencing surface amplification (Parker *et al.*, 2017; Loviknes *et al.*, 2024; Geyin and Maurer, 2023). Similarly, the geological age of formations has proven useful, as younger and unconsolidated sediments are generally associated with lower V_{s30} values, whereas older and more consolidated rocks, such as carbonates or crystalline units, yield higher velocities (Crespo *et al.*, 2022; Navarro *et al.*, 2025).

In Italy, interest in the detailed study of site effects has substantially grown following recent damaging earthquakes, such as the 2002 San Giuliano di Puglia event [M_w 5.7: Strollo *et al.* (2007); Puglia *et al.* (2013)], the 2009 L'Aquila earthquake [M_w 6.3: Tertulliani *et al.* (2012)], and the 2012 Emilia seismic sequence [M_w 6.1; Luzi *et al.* (2013)], which clearly demonstrated the critical role of local site conditions in amplifying shaking and controlling damage distribution. Following these earthquakes, the Italian Civil Protection Department launched large-scale seismic microzonation (SM) campaigns, producing a unique national dataset of geophysical measurements (Web MS-CLE, n.d). In recent years, Forte *et al.* (2019) developed a seismic soil classification map for Italy by averaging site-specific V_{s30} measurements for each geo-lithological

complex derived from a 1:100,000 geological map. Mori *et al.* (2020) produced a high-resolution Vs30 map by combining geomorphological classes with regression models based on slope and elevation, using the Italian SM dataset of 11,000 Vs profiles; more recently, Mori *et al.* (2026) calibrated another Vs30 map with the aid of machine learning techniques. In this work, we test the correlation between Vs30 and topographic and morphologic proxies that have not been used in previous works on a national scale in Italy.

On a regional scale, Gironelli *et al.* (2024) developed a Vs30 map for the Marche region (Italy) using a dual-proxy mixed-effect regression, where Vs30 was modelled as a function of reclassified lithological complexes from the 1:100,000 lithological map of Italy (ISPRA, 2021) proposed by the Istituto Superiore per la Protezione e la Ricerca Ambientale [the Italian Institute for Environmental Protection and Research (ISPRA)] and topographic slope. Importantly, the study demonstrated that the original 30-metre resolution could be resampled to 150 m without significant loss of variability in terms of Vs30.

On a global scale, beyond the United States Geological Survey global slope-based Vs30 map (Wald and Allen, 2007), Japan's Seismic Hazard Information Station derives amplification factors from nationwide engineering-geomorphologic classifications linked to Vs profiles (Wakamatsu and Matsuoka, 2011), and New Zealand's national Vs30 maps blend geology-based and terrain/slope-based models (Perrin *et al.*, 2015; Foster *et al.*, 2019).

Collectively, these studies confirm that incorporating geological/lithological information alongside morphometric variables is essential for multi-proxy approaches, leading to more accurate and regionally transferable Vs30 estimates.

In addition to these contributions, Stewart *et al.* (2014) performed one of the most comprehensive evaluations of geology- and terrain-based proxies for Vs30, using a database of 314 shear-wave velocity profiles from the Hellenic region. Their analysis showed that surface-geology categories, defined according to geologic age, material gradation, and depositional environment, provide substantially more accurate estimates of Vs30 than models based solely on terrain slope. More recently, Cultrera and Mercuri (2025) investigated site-effect indicators at stations of the Istituto Nazionale di Geofisica e Vulcanologia [the Italian National Institute of Geophysics and Volcanology (INGV)] seismic network and found that lithological information is significantly correlated with the spatial variability of site response. These findings further reinforce the importance of robust geological and lithological descriptors when analysing the variability of Vs30 on a national scale.

Building on these national and international experiences, the present study aims to investigate the correlation between Vs30 and a comprehensive set of site proxies on a national scale. Starting from the high-resolution national digital terrain model (DTM) TINITALY/1.1 (Tarquini *et al.*, 2023), we tested different spatial scales by resampling the DTM onto coarser grids. From these, we derived several indicators describing terrain shape and variability, such as *slope*, measures of landscape *roughness* and *curvature*, as well as geomorphological classes. To complement the terrain information, we also include independent geological data, specifically sediment thickness (Pelletier *et al.*, 2016) and lithological classifications from national sources (ISPRA, 2021; Bucci *et al.*, 2022).

The aim of this work is threefold: i) to test, for the Italian territory, the predictive performance of multiple morphometric and geological proxies against an extensive Vs30 database, so as to explain Vs30 variability; ii) to assess the ability of existing lithological maps to capture Vs30 variability; and iii) to propose a new lithological reclassification on a national scale, based on the ISPRA (2021) lithological map, that better reflects the spatial distribution of Vs30.

2. Data sources

2.1. Vs30 dataset

The velocity profiles in this study are derived from different data sources, such as SM studies, geodata sets of Italian regions, professional studies, and the Italian ACcelerometric Archive [ITACA: Felicetta *et al.* (2023)] database.

Approximately 15,000 shear-wave velocity (V_s) profiles were collected throughout Italy through active and passive surveys, employing both invasive and noninvasive techniques, as well as combined approaches. These profiles were obtained from geophysical measurements conducted using methods such as down-hole, cross-hole, seismic refraction (P- and S-wave methods), multi-channel analysis of surface waves (MASW) in both Love and Rayleigh waves (Park *et al.*, 1999; Safani *et al.*, 2005), spatial autocorrelation (SPAC) and derivative approaches (Aki, 1957; Asten, 2006; Stephenson *et al.*, 2009), and refraction microtremor [ReMi: Louie (2001)].

Fig. 1a illustrates the spatial distribution of the V_s30 values, where low values are represented in blue and high values in red. Fig. 1b shows the main geographic and physiographic features and administrative regions referenced in the paper. The final dataset contains a few V_s30 profiles with high values (rock sites), which are primarily located along the Apennine arc, south-eastern Sicily, the Alps, and the Puglia region. The lowest V_s30 values are predominant in the Po Plain and coastal areas, as expected.

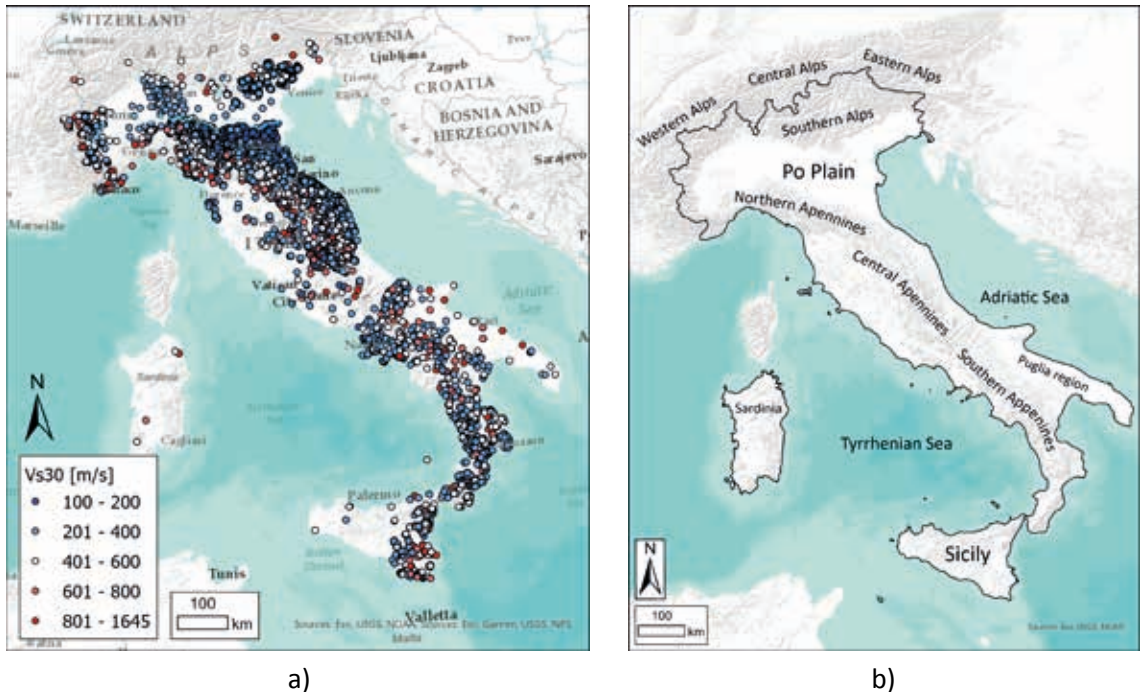


Fig. 1 - a) Spatial distribution of the V_s30 dataset. b) Map of the main geographic and physiographic features and administrative regions referenced in the paper.

The histogram of the 10-base logarithm of Vs30, shown in Fig. 2, reveals a bimodal distribution, with a first peak around 2.4 ($Vs30 \approx 250$ m/s) and a second peak near 2.6 ($Vs30 \approx 400$ m/s). This pattern reflects the presence of profiles acquired in fine-grained deposits, medium to coarse-grained deposits, and rocks affected by fracturing and/or alteration. The distinction among these geological features underscores the importance of accounting for lithological contribution when analysing Vs30.

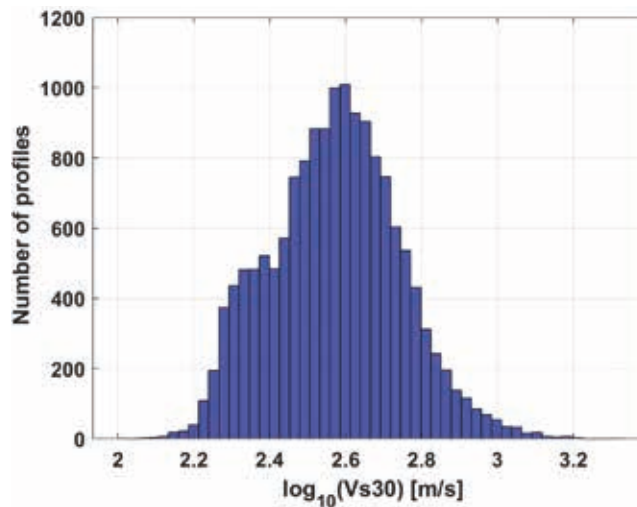


Fig. 2 - Histogram of $\log_{10}(Vs30)$.

2.2. Lithological maps

Lithology captures essential information about the composition and physical and mechanical characteristics of rocks and soils, making it a crucial factor in understanding the Earth's surface and subsurface processes. Lithological data is typically derived from geological maps and substantial efforts have been made in recent years to improve global accessibility to high-quality geological datasets (EPOS, n.d.).

In Italy, geological maps having nationwide coverage are available at scales of 1:1,250,000 (Bonomo *et al.*, 2005), 1:1,000,000 (Compagnoni, 2004; Cipolloni *et al.*, 2009; Pantaloni, 2011), 1:500,000 (Compagnoni *et al.*, 1976–1983), and 1:100,000 (ISPRA, 2020), all distributed by ISPRA (Delogu *et al.*, 2012). Additionally, ISPRA coordinates and publishes the 1:50,000 geological map of Italy, although it currently offers only partial coverage of the national territory. In particular, the digital 1:100,000 lithological map was released in 2021, based on the 277 sheets of the geological map of Italy (ISPRA, 2020); it provides a consistent lithological representation, of the entire country, with no discontinuities at map borders, subdivided into 50 classes identified from geological descriptions and age, whose detailed descriptions are reported in Table A1 of Appendix A. This effort resulted in a single shapefile, which is accessible through web services (ISPRA, 2021).

An alternative lithological map of Italy at a 1:100,000 scale was proposed by Bucci *et al.* (2021, 2022) and derived from the nationwide 1:100,000 geological map of Italy (ISPRA, 2020). The 300,000 polygons are classified into 19 classes according to compositional and geomechanical criteria.

2.3. Average soil and sedimentary deposit thickness map

Pelletier *et al.* (2016) released a high-resolution global dataset (30 arcsec, ~1 km) of soil, intact regolith (heterogeneous material covering solid bedrock), and sedimentary deposit thicknesses above unweathered bedrock, with a maximum thickness of 50 m. The dataset distinguishes between hillslopes, valley bottoms, and lowlands, using optimised models for each landscape type. Thickness estimates are calibrated and validated with independent data: soil thickness measurements from the U.S. and Europe for hillslopes, and depth-to-bedrock observations from groundwater wells in the U.S. for lowlands.

2.4. Digital elevation model and topographic indices

In this study, the TINITALY/1.1 DTM, developed by Tarquini *et al.* (2023) was used. It covers the entire Italian territory, as the primary source of elevation data on the national scale. This model provides a consistent representation of the surface topography, enabling us to derive slope values and related morphometric variables uniformly across the study area. It features a spatial resolution of 10 m × 10 m and is available in GeoTIFF format, georeferenced using the UTM WGS 84 zone 32N coordinate system (INGV Sezione di Pisa, n.d.).

The TINITALY/1.1 DTM, originally available with a spatial resolution of 10 m × 10 m (Tarquini *et al.*, 2023), was downsampled to four different spatial resolutions (150 m, 250 m, 500 m, and 1,000 m) using the resample tool in ArcGIS Pro 3.4.2 (Esri Inc., 2024) with the Nearest Neighbour algorithm. No additional filtering or smoothing was applied. This resampling strategy was adopted to evaluate which spatial scale provides the best correlation between terrain-derived proxies and Vs_{30} , while preserving the original elevation values and avoiding any interpolation-induced modification of the DEM.

For each resolution, *elevation* was directly extracted from the resampled DEM and the following topographic indices were computed using ArcGIS Pro 3.4.2 (see Table 1 for the definitions of these metrics): i) *slope*, ii) terrain ruggedness index (*TRI*), iii) vector ruggedness measure (*VRM*), iv) topographic position index (*TPI*), v) *profile curvature*, vi) *plan curvature*, vii) *standard curvature*, and viii) geomorphological classes. The *TRI* is calculated using the GDALDEM Roughness function of the Geospatial Data Abstraction Library (GDAL Development Team, 2021), available in QGIS 3.22.11 (QGIS Development Team, 2022).

Slope quantifies the rate of *elevation* change in the direction of the steepest gradient for each DEM cell. As the first derivative of the DEM, it describes the steepness of the terrain at any given point (Fig. 3).

The *TRI* (Fig. A1), introduced by Riley *et al.* (1999), is a measure of terrain roughness that quantifies topographic heterogeneity in a DTM. The *TRI* is widely used in ecological modelling, hydrology, and geomorphology to assess terrain complexity and habitat suitability. Higher *TRI* values indicate rugged or highly variable terrain, while lower values represent flat or smooth surfaces.

The *VRM* (Fig. A2), introduced by Sappington *et al.* (2007), analyses the three-dimensional variability in the orientation of surface normals, which are vectors perpendicular to the terrain. For each grid cell in a DTM, the average direction of the normals from the focal cell and surrounding eight neighbouring cells is calculated. The magnitude of the resultant vector indicates the degree of alignment of the normals for the nine cells. Subtracting this magnitude from 1 produces a dimensionless ruggedness index that ranges from 0 (flat surface) to 1 (highly rugged surface).

Terrain *roughness* (Fig. A3), following Hobson (1972) and Wilson *et al.* (2007), is defined as the maximum *elevation* difference between a focal cell and its surrounding eight neighbouring

Table 1 - Summary of the topographic proxies adopted in this study, including their formal definitions, units, and value ranges. All topographic indices (*slope*, *TRI*, *VRM*, *TPI*, curvatures, and geomorphological classes) were computed from the DEM at a spatial resolution of 150 m × 150 m; therefore, the reported ranges refer to this resolution.

Topographic proxies	Formal definition	Units	Range
<i>Slope</i>	Local terrain slope expressed as the inclination angle with respect to the horizontal plane.	degrees (°)	0–86
<i>TRI</i> (Riley <i>et al.</i> , 1999)	$TRI = \sqrt{\sum (x_i - x_0)^2}$ where x_0 is the elevation of the central cell and x_i represents the elevation of each of the eight neighbouring cells.	m	0–6,768
<i>Roughness</i> (Hobson, 1972)	Maximum <i>elevation</i> difference between a focal cell and its eight surrounding neighbouring cells.	m	0–3,480
<i>VRM</i> (Sappington <i>et al.</i> , 2007)	$VRM = 1 - \frac{\sqrt{(\sum_{i=1}^N x_i)^2 + (\sum_{i=1}^N y_i)^2 + (\sum_{i=1}^N z_i)^2}}{N}$ where x_i , y_i and z_i are the components of the unit vector normal to the surface at the i -th cell, computed as: $x_i = \sin(\text{slope}_i) \times \sin(\text{aspect}_i)$ $y_i = \sin(\text{slope}_i) \times \cos(\text{aspect}_i)$ $z_i = \cos(\text{slope}_i)$ where <i>aspect</i> is the compass direction that a slope faces and N is the number of cells in the moving window ($N = 9$ for a 3×3 window). <i>VRM</i> is computed from the sum of the unit normal vectors within the 3×3 cell moving window and assigned to the central cell.	–	0–0.4
<i>TPI</i> (Weiss, 2001)	$TPI = x_0 - \bar{x}$ where x_0 is the <i>elevation</i> of the central cell and \bar{x} is the mean <i>elevation</i> of the eight neighbouring cells within the 3×3 window.	m	–1,691–1,265
<i>Standard curvature</i> (Moore <i>et al.</i> , 1991; Zevenbergen and Thorne, 1987)	$k = 100 \times \left(\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right)$ The sum of the second derivatives of <i>elevation</i> with respect to the horizontal coordinates.	m ^{–1}	–30×10 ^{–2} – 15.3×10 ^{–2}
<i>Profile curvature</i> (Moore <i>et al.</i> , 1991; Zevenbergen and Thorne, 1987)	Curvature calculated along the direction of maximum slope.	m ^{–1}	–15.8×10 ^{–2} – 15.2×10 ^{–2}
<i>Planform curvature</i> (Moore <i>et al.</i> , 1991; Zevenbergen and Thorne, 1987)	The curvature of the surface perpendicular to the direction of maximum slope.	m ^{–1}	–14.8×10 ^{–2} – 5.4×10 ^{–2}
Geomorphological classes (Jasiewicz and Stepinski, 2013)	Geomorphological classification derived from a DEM by analysing how <i>elevation</i> increases or decreases along the eight main directions around each cell: flat (1), peak (2), ridge (3), shoulder (4), spur (5), slope (6), hollow (7), footslope (8), valley (9), and pit (10).	–	–

cells. High *roughness* values indicate a highly irregular or rugged terrain with significant *elevation* differences, such as mountainous or rocky areas. Low *roughness* values represent smoother, more homogeneous surfaces, such as plains or gently rolling landscapes.



Fig. 3 - Slope map expressed in degrees and calculated with a spatial resolution of 150 m; the average value is 9.4°.

The *TPI* (Fig. A4), proposed by Weiss (2001), quantifies the relative *elevation* of a focal cell compared to the average *elevation* of its surrounding neighbourhood. A positive *TPI* indicates that the focal cell is higher than its surrounding cells, characterising ridges, peaks, or elevated landforms. Conversely, a negative *TPI* suggests that the cell is lower than its surrounding cells, identifying depressions, valleys, or concave features. Values near zero imply that the cell has a similar *elevation* to the average of its neighbourhood, corresponding to relatively flat or uniform slopes.

The *profile curvature* (Fig. A5) measures the amount of slope change along a downhill flow path, indicating whether water will speed up or slow down due to the slope's concavity or convexity. A positive *profile curvature* reveals that the surface is upwardly concave (like a valley), which decelerates flow and encourages deposition; a negative value indicates that the surface is upwardly convex (like a hilltop), accelerating flow and promoting erosion.

The *planform curvature* (Fig. A6) (commonly known as *plan curvature*) represents the curvature measured perpendicularly to the direction of the maximum slope. Positive values indicate areas where surface flow diverges, while negative values correspond to zones of converging flow. When *plan curvature* is positive, the surface is convex in the direction perpendicular to the slope, whereas a negative value signifies concavity in the same orientation. A curvature value of zero indicates a flat surface in the analysed direction.

The *standard curvature* (Fig. A7) combines both profile and *planform curvature* into a single metric that summarises overall surface curvature. Analysing the two orthogonal components

(*profile* and *planform curvature*) together help interpret water movement across the terrain and, consequently, soil deposition dynamics.

The geomorphological classes (Fig. A8 and Table 1) are identified following the approach proposed by Jasiewicz and Stepinski (2013). They provide a representation of the landscape based on variations in *elevation* within the local neighbourhood of a target cell. In total, we obtained 498 distinct geomorphon patterns.

Table 2 summarises the Vs30 proxies analysed in this study, grouped into categorical and numeric variables.

Table 2 - Vs30 proxies analysed in this study, grouped into categorical and numeric variables.

Categorical proxies	Numeric proxies
Lithological maps (ISPRA, 2021; Bucci <i>et al.</i> , 2021, 2022); geomorphological classes (Jasiewicz and Stepinski, 2013).	<i>Elevation; slope; roughness; TRI; VRM; TPI; profile curvature; planform curvature; standard curvature; average soil and sediment thickness (Pelletier et al., 2016).</i>

3. Statistical analyses

Statistical analyses were performed separately for numerical and categorical variables. In particular, the following statistical indices were used to quantify the relationships between Vs30 and the identified proxies (topographic indexes and lithology):

- Pearson correlation coefficient (r) (Pearson, 1895) measures the linear correlation between two numerical variables. It ranges from -1 to 1, where 1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation, and 0 indicates no linear correlation;
- eta-square (η^2) index (Fisher, 1925) quantifies the relationship between numerical and categorical variables from the proportion of variance in a numerical variable explained by a categorical variable. It ranges from 0 to 1, where 0 means that the categorical variable does not explain any variation in the numerical variable and 1 means that the categorical variable fully explains the variance in the numerical variable.

3.1. Numerical variables

The slope angle in degrees was converted to its tangent, following Wald and Allen (2007); hereinafter, the term slope refers to this quantity. Pearson correlation coefficients were computed between $\log_{10}(Vs30)$ and all numerical proxies, repeating the analysis at four spatial resolutions. *TPI*, *standard curvature*, *planform curvature*, and *profile curvature* exhibit only weak linear correlation with $\log_{10}(Vs30)$, with $|r| \leq 0.15$ at all four spatial resolutions, and were therefore not considered as candidate predictors.

We, then, examined in more detail the relationship between $\log_{10}(Vs30)$ and the deposit thickness. Among the products provided by Pelletier *et al.* (2016), we specifically used the raster *Average_soil_and_sedimentary-deposit_thickness.tif*. This global-scale dataset, originally provided at a spatial resolution of approximately 1 km, represents the weighted-average thickness of soil and sedimentary deposits within each grid cell and describes the thickness of relatively porous and unconsolidated materials overlying unweathered geological bedrock, up

to a maximum depth of 50 m (Fig. A9). This depth range is sufficient to investigate potential relationships with Vs_{30} . However, it should be noted that this map was developed to support hydrological and ecosystem models; therefore, its objectives differ from those of seismic site characterisation. In addition, in the Italian territory, sediment thickness is known to significantly vary at spatial scales much smaller than 1 km².

A negative Pearson correlation, consistent with expectations, is observed between $\log_{10}(Vs_{30})$ and sediment thickness ($r = -0.58$). However, Fig. 4 shows that the values are mainly clustered into two deposit thickness classes (0–15 m and ≥ 50 m), with very few intermediate values. A detailed analysis of the raster value distribution over Italy shows that the thickness variable is strongly concentrated in a few recurring discrete values. About 43% of the Italian pixels are assigned a thickness of 1 m and about 15% a thickness of 50 m, so that nearly 60% of the national coverage falls into only two thickness values.

A sensitivity analysis indicates that the observed correlation is controlled by these two dominant end-member classes. When the two most populated thickness values (1 m and 50 m) are excluded, the Pearson correlation decreases from -0.58 to about -0.19 . This shows that the global correlation is influenced by these two clusters.

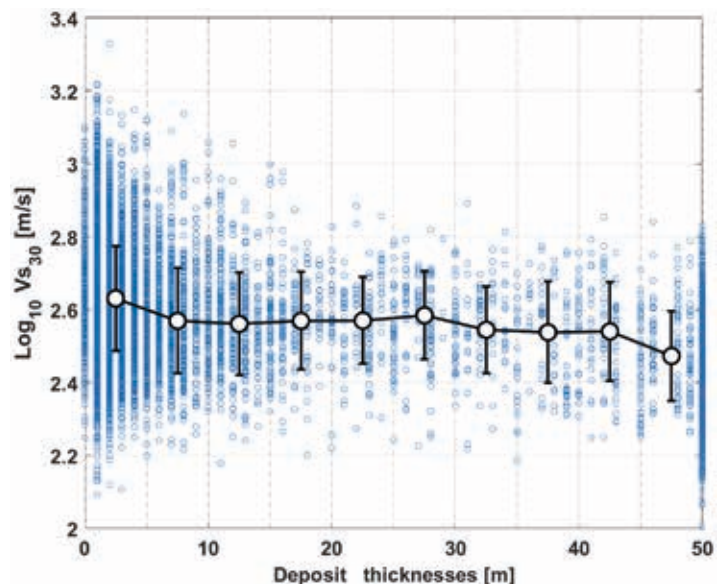


Fig. 4 - Scatter plot of $\log_{10}(Vs_{30})$ versus the deposit thickness (metres) derived from Pelletier *et al.* (2016). The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

For the remaining numerical topographic proxies (*TRI*, *elevation*, *roughness*, *slope*, and *VRM*), the correlation is found to be enhanced when Vs_{30} and the numerical variable are expressed in a \log_{10} scale, after replacing zero values with small positive constants. This transformation was adopted because both Vs_{30} and the morphometric proxies considered exhibit bimodal log-normal distributions; applying \log_{10} reduces skewness, stabilises variance, and produces more symmetric distributions, enabling the Pearson correlation coefficient to provide a more reliable measure of association while also reducing the influence of extreme values.

Table 3 and Fig. 5 show the statistical relationships between $\log_{10}(Vs_{30})$ and the numerical proxies considered expressed by the Pearson correlation coefficient. $\log_{10}(Vs_{30})$ is positively correlated with \log_{10} of five topographic indices (*TRI*, *elevation*, *roughness*, *slope*, and *VRM*) across all four spatial resolutions analysed.

Table 3 - Summary of the statistical relationships between $\log_{10}(Vs30)$ and the numerical proxies considered. For each proxy, the table reports the Pearson correlation coefficient together with the lower and upper bounds of the 95% confidence interval (CI).

Proxies	Pearson r	95% CI (lower)	95% CI (upper)
\log_{10} TRI 150 m	0.61	0.6	0.62
\log_{10} TRI 250 m	0.62	0.61	0.63
\log_{10} TRI 500 m	0.62	0.61	0.63
\log_{10} TRI 1,000 m	0.62	0.61	0.63
\log_{10} elevation 150 m	0.62	0.61	0.63
\log_{10} elevation 250 m	0.62	0.61	0.63
\log_{10} elevation 500 m	0.62	0.61	0.63
\log_{10} elevation 1,000 m	0.62	0.61	0.63
\log_{10} roughness 150 m	0.61	0.6	0.62
\log_{10} roughness 250 m	0.62	0.61	0.63
\log_{10} roughness 500 m	0.62	0.61	0.63
\log_{10} roughness 1,000 m	0.63	0.62	0.64
\log_{10} tan(slope) 150 m	0.6	0.59	0.61
\log_{10} tan(slope) 250 m	0.6	0.59	0.61
\log_{10} tan(slope) 500 m	0.6	0.59	0.61
\log_{10} tan(slope) 1,000 m	0.61	0.59	0.62
\log_{10} VRM 150 m	0.58	0.57	0.59
\log_{10} VRM 250 m	0.58	0.57	0.59
\log_{10} VRM 500 m	0.59	0.58	0.6
\log_{10} VRM 1,000 m	0.59	0.58	0.6

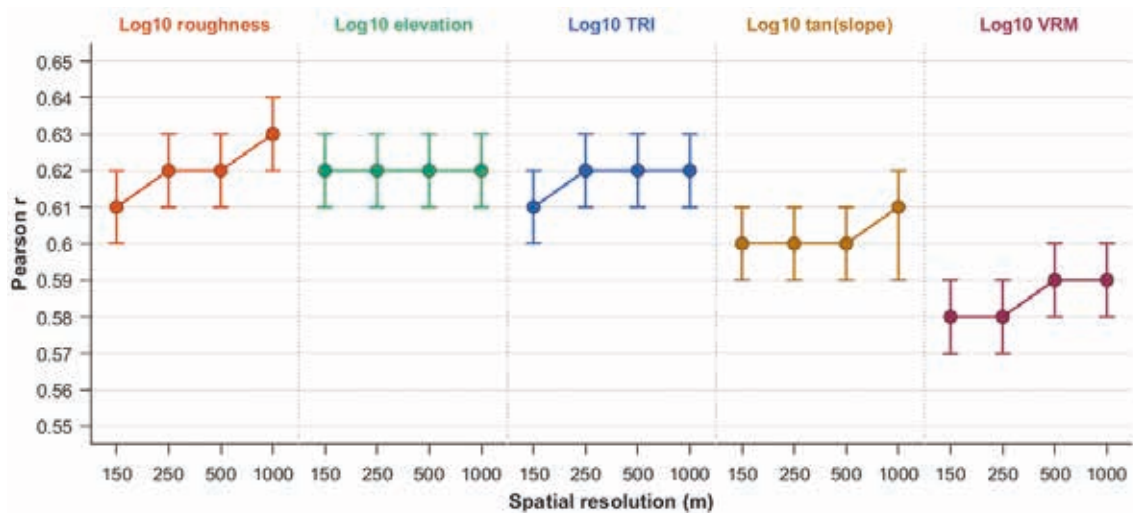


Fig. 5 - Graphical summary of the statistical relationships between $\log_{10}(Vs30)$ and the numerical proxies considered. For each proxy and spatial resolution, the Pearson correlation coefficient (r) is shown together with its 95% confidence interval (CI).

The narrow 95% confidence intervals (CIs) indicate highly robust correlation estimates, mainly due to the large sample size. All reported correlations are associated with p values well below 0.01, confirming their strong statistical significance. The four topographic proxies, $\log_{10}(TRI)$, $\log_{10}(elevation)$, $\log_{10}(roughness)$, and $\log_{10}(slope)$, exhibit a similar one-dimensional trend with $\log_{10}(Vs30)$ (see Figs. A10 to A12 and Fig. 6) and are highly correlated with one another (see Fig. A14). $\log_{10}(VRM)$, instead, shows a trend with $\log_{10}(Vs30)$ that differs from the other topographic proxies (Fig. A13).

Correlation results indicate that all log-transformed topographic proxies considered (TRI , $elevation$, $roughness$, $slope$, and VRM) exhibit moderate correlation with $\log_{10}(Vs30)$, with Pearson coefficients generally ranging between about 0.58 and 0.63.

Differences among proxies are relatively small, and the corresponding 95% CIs largely overlap, indicating comparable predictive strength across the tested metrics. Considering the results across all four spatial resolutions, $\log_{10}(roughness)$ and $\log_{10}(elevation)$ show the highest correlation values overall, closely followed by $\log_{10}(TRI)$, while $\log_{10} \tan(slope)$ and $\log_{10}(VRM)$ exhibit slightly lower correlations.

A slight but systematic increase in correlation with increasing spatial window size is observed for most proxies, except for $elevation$. However, the improvement is modest, typically in the order of a few hundredths in Pearson r . This behaviour probably reflects a reduction of small-scale topographic noise at coarser resolutions, which produces more stable terrain metrics.

Overall, these results support the use of several topographic metrics as viable candidate predictors, without indicating a single clearly dominant proxy or resolution.

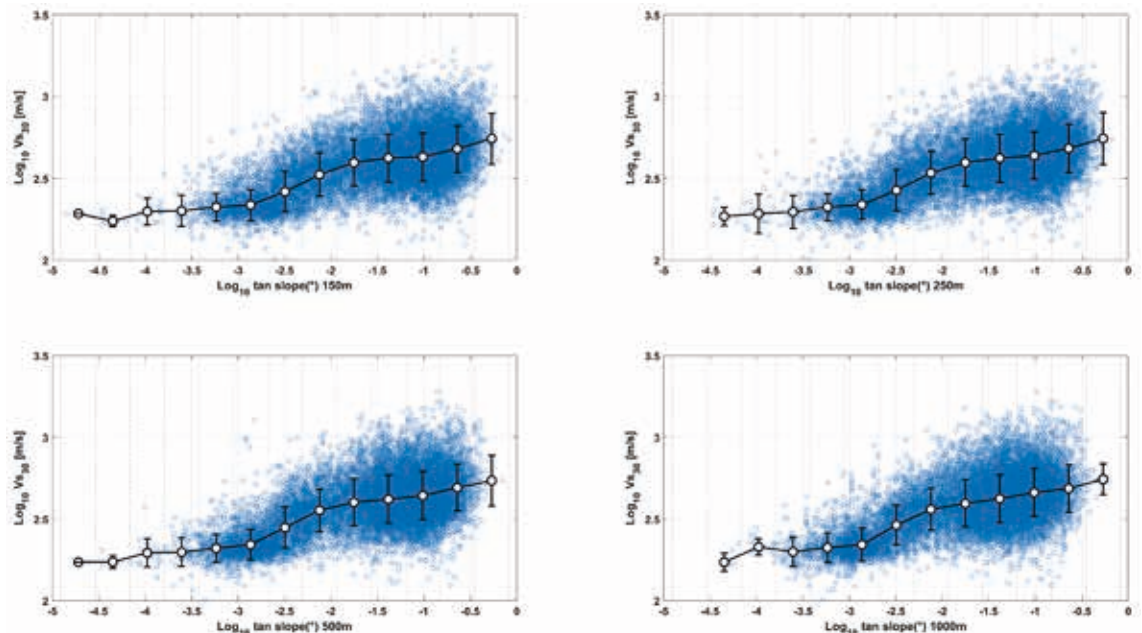


Fig. 6 - Scatter plot between $\log_{10}(Vs30)$ [m/s] and $\log_{10}(slope)$ at four different resolutions. The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

3.2. Categorical variables

The geomorphological classification shows η^2 values of about 0.33 at all investigated spatial resolutions, indicating a moderate correlation with $\log_{10}(Vs30)$. Regardless of this, it was not retained among the best proxy predictors. This decision is motivated by the fact that the largest contribution to the explained variance is attributed to the flat geomorphology class, which includes about one-fourth of the available Vs profiles and is separated by the rest of the classes in terms of mean Vs30 (Fig. 7). When the flat class is excluded, η^2 sharply decreases to about 0.02–0.03 across all spatial resolutions, indicating that the between-group variance component becomes very small compared to the total variance. This means that the remaining geomorphological classes have very similar mean $\log_{10}(Vs30)$ values and, therefore, provide limited discriminating power.

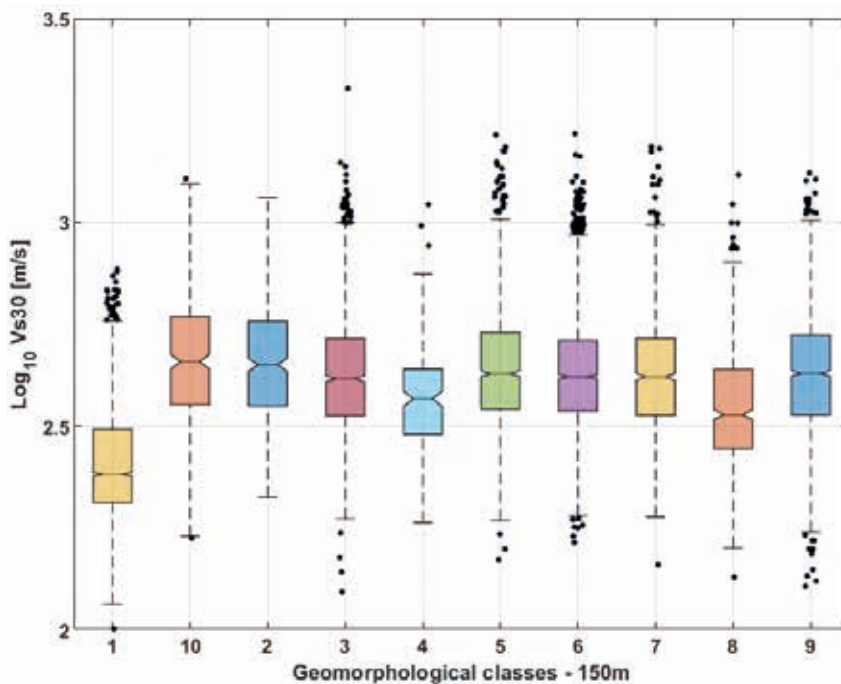


Fig. 7 - Box and whisker plot of $\log_{10}(Vs30)$ across geomorphological classes derived from a spatial resolution of 150 m. Landform types: 1) flat, 2) peak, 3) ridge, 4) shoulder, 5) spur, 6) slope, 7) hollow, 8) footslope, 9) valley, and 10) pit.

Since the η^2 values associated with the lithological maps proposed by ISPRA (2021) and Bucci *et al.* (2022) are 0.24 and 0.22, respectively, we performed statistical tests to evaluate the ability of different lithological classifications to explain the variability of $\log_{10}(Vs30)$. These analyses were conducted to quantify how effectively the existing national-scale lithological maps (ISPRA, 2021; Bucci *et al.*, 2022) capture the variability in $\log_{10}(Vs30)$ and to assess whether an improved aggregation scheme could better represent this variability.

To this end, one-way Analysis of Variance (ANOVA) tests were performed between $\log_{10}(Vs30)$ and the lithological classes proposed by ISPRA (2021) and Bucci *et al.* (2022). In the ANOVA framework, the F -statistic is calculated as the ratio between the variance among groups (mean square between) and the variance within groups (mean square within). A high F -value indicates

that the variability between groups is significantly greater than the variability within groups, suggesting that the observed differences are unlikely to be due to random chance.

The ISPRA (2021) lithological map is primarily based on lithological descriptions and geological age and includes approximately 50 classes, whereas the map proposed by Bucci *et al.* (2022) consists of 19 classes defined according to compositional and geomechanical criteria. Based on these considerations, a new lithological map was developed from the ISPRA (2021) classification by aggregating the original 50 classes using geophysical criteria to better capture the variability of $\log_{10}(Vs30)$ across different lithological groups.

To identify which lithological units of the ISPRA (2021) map could be statistically aggregated, we initially performed a pairwise Welch *t*-test (Welch, 1947) on $\log_{10}(Vs30)$ values for all possible pairs of the 50 original ISPRA lithological classes. The test was used as a preliminary screening tool to identify class pairs with statistically similar mean values. Only one lithological class, E2, has not been considered in the test, because it contains only one profile.

The original 50 ISPRA lithological classes were, then, aggregated into 11 broader groups. The aggregation was primarily guided by lithological criteria, taking into account the Welch *t*-test results on the similarity between class means. For classes represented by a limited number of measurements, grouping was mainly based on lithological criteria.

The resulting lithological grouping (Fig. 8 and Table 4) consists of:
eight classes for rocks:

- limestone and dolomites (LIDO)
- magmatic rocks and metamorphic rocks (IMR)
- effusive magmatic rocks (EMR)
- limestone-marly (LM)
- cemented and coarse sediments (CCS)
- sandstones, pelitic-arenaceous complexes, calcareous arenaceous complexes, conglomerates, travertine, quartzarenites (ARTR)
- pyroclastic rocks (PYR)
- argillites, siltstones, marls (ASM);

one class for volcanic pyroclastic deposits (PYD);

two classes for soils:

- coarse-to-medium-grained soils (SMG)
- fine grained soils (FGS).

Table 4 - Lithological codes from the new classification scheme showing the correspondence between each aggregated group and the original ISPRA (2021) lithological classes.

Lithological code	ISPRA code
CCS	A14
ARTR	A5, A8, A4, A9, A10, A15, A11
EMR	D1, D2, D3, D4
PYR	C2, D5
FGS	B1, B5
SMG	B4, B7, N1, N2, N3, A13, B2, B6, B3
PYD	D6, D8, D7
LIDO	A1, A2, G2, G3
IMR	E1, E2, E3, F1, F2, F3, F4, F5, G1, G4, G5, H1, H2
ASM	A7, C1, A12, A6
LM	A3



Fig. 8 - Proposed lithological classification derived from the 50 original classes of the ISPRA (2021) lithological map.

To evaluate the effectiveness of the lithological classifications in explaining $\log_{10}(Vs30)$ variability, we performed one-way ANOVA tests on the original ISPRA (2021) classification, the aggregation proposed by Bucci *et al* (2022), and the newly developed lithological classification; the F values (Table 5) indicate that the proposed lithological classification provides the highest level of discrimination among the three tested maps.

Table 5 - Results of the one-way ANOVA tests performed on the three lithological classifications (ISPRA, 2021; Bucci *et al.*, 2022; and the proposed classification). The table reports the F values and corresponding p values.

Lithological classification	F value	p value
ISPRA (2021)	125.6	< 0.05
Bucci <i>et al.</i> (2022)	244.6	< 0.05
Proposed classification	380.4	< 0.05

Specifically, the ANOVA applied to the new lithological classification yields an F value of 380.4 with a p value lower than 0.05 (Fig. 9), indicating that the variability of $\log_{10}(Vs30)$ between lithological classes is substantially greater than the variability within the classes. This F value is significantly higher than the values obtained for the classification proposed by Bucci *et al.* (2022) ($F = 244.6$, $p < 0.05$) and for the original ISPRA (2021) classification ($F = 125.6$, $p < 0.05$).

Although all three lithological groupings show statistically significant relationships with $\log_{10}(Vs30)$, the higher F values indicate that the newly defined lithological classes capture the variability in $\log_{10}(Vs30)$ more effectively, providing a more robust basis for future regression analyses and large-scale $Vs30$ mapping.

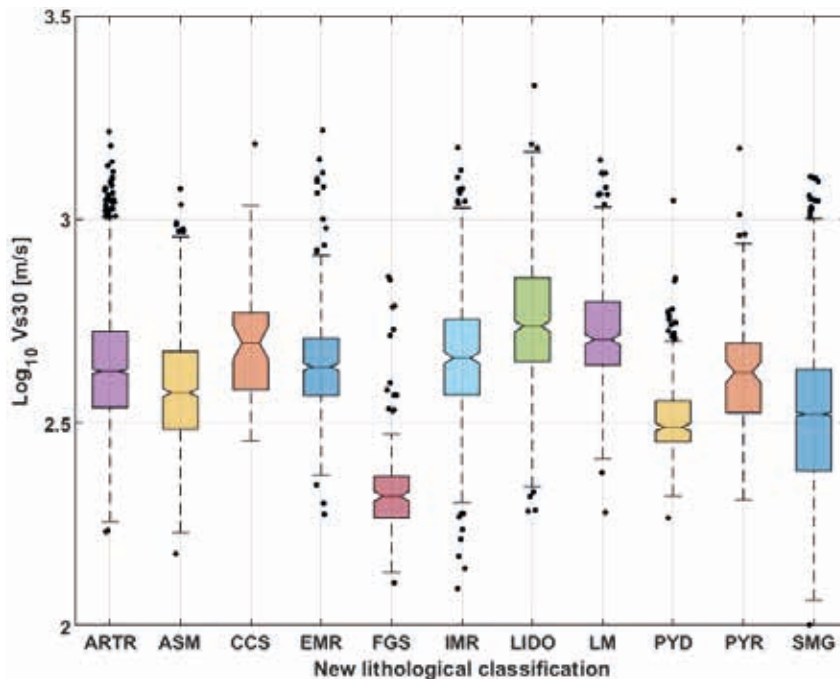


Fig. 9 - Box and whisker plot showing the variability of $\log_{10}(Vs30)$ across the new lithological classification.

4. Discussion and conclusions

This study has focused on evaluating the predictive capability of lithological and geomorphological proxies for shear-wave velocity in the uppermost 30 m ($Vs30$) in Italy. We compiled a dataset of approximately 15,000 shear-wave velocity profiles, evenly distributed across the Italian territory and examined the availability of existing nationwide proxies for $Vs30$ with the long-term goal of calibrating a $Vs30$ map.

Two lithological maps, both ultimately derived from the 1:100,000 geological map of Italy, are available (ISPRA, 2020). The first is the map released by ISPRA (2021), which classifies the geological units into 50 lithological classes. The second is the alternative map proposed by Bucci *et al.* (2022), which reclassifies the original geological units into 19 categories according to compositional and geomechanical criteria.

We selected the 10 m \times 10 m DEM by Tarquini *et al.* (2023) and calculated 10 topographic indices at four different resolutions (150 m, 250 m, 500 m, and 1,000 m). Additionally, we considered the soil thickness map by Pellettieri *et al.* (2016), which is globally calibrated at a resolution of approximately 1 km².

Our results indicate that $\log_{10}(Vs30)$ is positively correlated with the \log_{10} of five topographic indices (*TRI*, *elevation*, *roughness*, *slope* expressed as the tangent of the slope angle, and *VRM*) across all four spatial resolutions analysed, with Pearson coefficients generally between about

0.58 and 0.63. In contrast, sediment thickness derived from the global dataset of Pelletier *et al.* (2016) shows a moderate negative correlation with $\log_{10}(Vs30)$, although the Vs30 observations are predominantly clustered within two thickness intervals (0–15m and > 50 m).

The correlation of topographic proxies (*TRI*, *elevation*, *roughness*, *slope*, and *VRM*) with Vs30 have 95% CIs which largely overlap, indicating comparable predictive strength. Across the four tested spatial resolutions, $\log_{10}(\textit{roughness})$ and $\log_{10}(\textit{elevation})$ show the highest correlations with $\log_{10}(Vs30)$, closely followed by $\log_{10}(TRI)$, whereas $\log_{10} \tan(\textit{slope})$ and $\log_{10}(VRM)$ yield slightly lower values. A small increase in correlation is observed at coarser spatial windows (except for *elevation*), typically limited to a few hundredths in Pearson *r*. This trend is consistent with the findings of Allen and Wald (2009) for *slope*–Vs30 relationships and likely reflects the reduction of small-scale topographic noise at coarser resolutions, leading to more stable terrain metrics. Moreover, since a substantial proportion of Vs profiles are in flat areas characterised by low topographic variability, resampling the raster to coarser resolutions produces only minor changes in the derived terrain metrics, thereby preserving the overall correlation pattern.

TPI, *standard*, *planform*, and *profile curvature* show only weak linear correlations with $\log_{10}(Vs30)$ ($|r| \leq 0.15$ at all tested resolutions) and were, therefore not considered as suitable predictors. The geomorphological classification shows moderate η^2 values (about 0.33), but this effect is mainly driven by the “flat” class; excluding it, η^2 reduces to about 0.02–0.03, highlighting the limited explanatory power of the remaining classes.

Finally, we calibrated a Vs30-oriented lithological map derived from the original ISPRA (2021) map by aggregating the 50 initial classes into 11 broader groups, primarily based on lithological criteria and supported by statistical screening of differences in mean $\log_{10}(Vs30)$ values.

The proxies identified will be used to calibrate a preliminary nationwide Vs30 model (Brunelli, 2025), although we acknowledge several limitations. First, the absence of Vs profiles in rock units, since geophysical tests are generally performed on soils. Moreover, the use of a more detailed geological map, such as the nationwide 1:50,000 scale, could improve the detection of smaller soil units, although this map is not yet available for the entire country.

The ongoing availability of new data, including Vs profiles, geological maps, and seismological studies, renders the development of a Vs30 model highly dynamic. Such a model would necessitate the coordinated efforts of academic researchers and industry to ensure its accuracy and adaptability.

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Appendix A



Fig. A1 - TRI map calculated with a spatial resolution of 150 m. The raster has a minimum value of 0, a maximum value of 6,768 m, and an average value of 78 m.



Fig. A2 - VRM map calculated with a spatial resolution of 150 m. The raster has a minimum value of 0, a maximum value of 0.4, and an average value of 0.006.



Fig. A3 - Roughness map calculated with a spatial resolution of 150 m. The raster has a minimum value of 0, a maximum value of 3,480, and an average value of 74.



Fig. A4 – *TPI* map calculated with a spatial resolution of 150 m. The raster has a minimum value of -1,691 m, a maximum value of 1,265 m, and an average value of 2.52 m.



Fig. A5 - *Profile curvature* map calculated with a spatial resolution of 150 m. The raster has a minimum value of $-15.8 \times 10^{-2} \text{ m}^{-1}$, a maximum value of $15.2 \times 10^{-2} \text{ m}^{-1}$, an average value of $0.005 \times 10^{-2} \text{ m}^{-1}$, and a standard deviation of $0.13 \times 10^{-2} \text{ m}^{-1}$.



Fig. A6 - *Plan curvature* map calculated with a spatial resolution of 150 m. The raster has a minimum value of $-14.8 \times 10^{-2} \text{ m}^{-1}$, a maximum value of $5.4 \times 10^{-2} \text{ m}^{-1}$, an average value of $0.005 \times 10^{-2} \text{ m}^{-1}$, and a standard deviation of $0.15 \times 10^{-2} \text{ m}^{-1}$.



Fig. A7 - *Standard curvature* map calculated with a spatial resolution of 150 m. The raster has a minimum value of $-30 \times 10^{-2} \text{ m}^{-1}$, a maximum value of $15.3 \times 10^{-2} \text{ m}^{-1}$, an average value close to zero, and a standard deviation of $0.25 \times 10^{-2} \text{ m}^{-1}$.

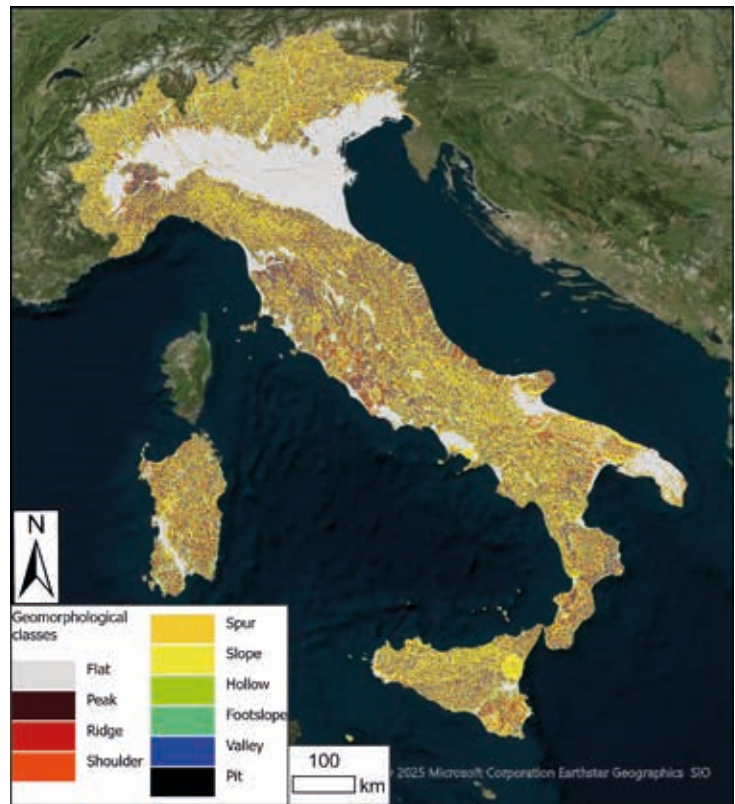


Fig. A8 - Geomorphological class map calculated with a spatial resolution of 150 m.



Fig. A9 - Average soil and sedimentary deposit thickness [m] map as proposed by Pelletier *et al.* (2016).

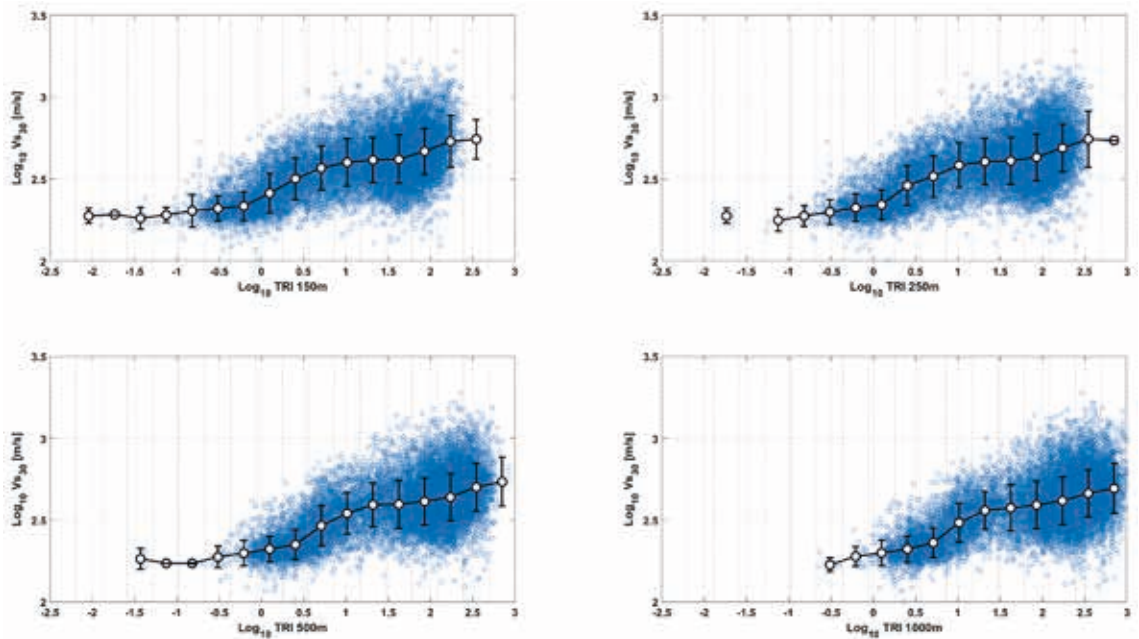


Fig. A10 - Scatter plot between $\log_{10}Vs_{30}$ [m/s] and $\log_{10}(TRI)$. The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

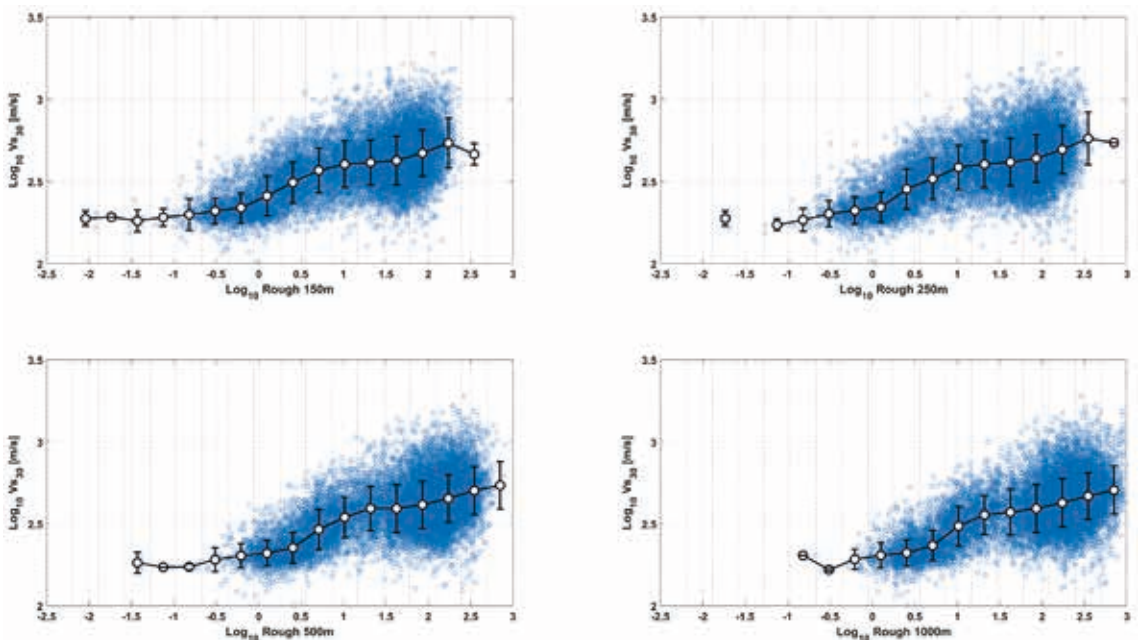


Fig. A11 - Scatter plot between $\log_{10}Vs_{30}$ [m/s] and $\log_{10}(roughness)$. The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

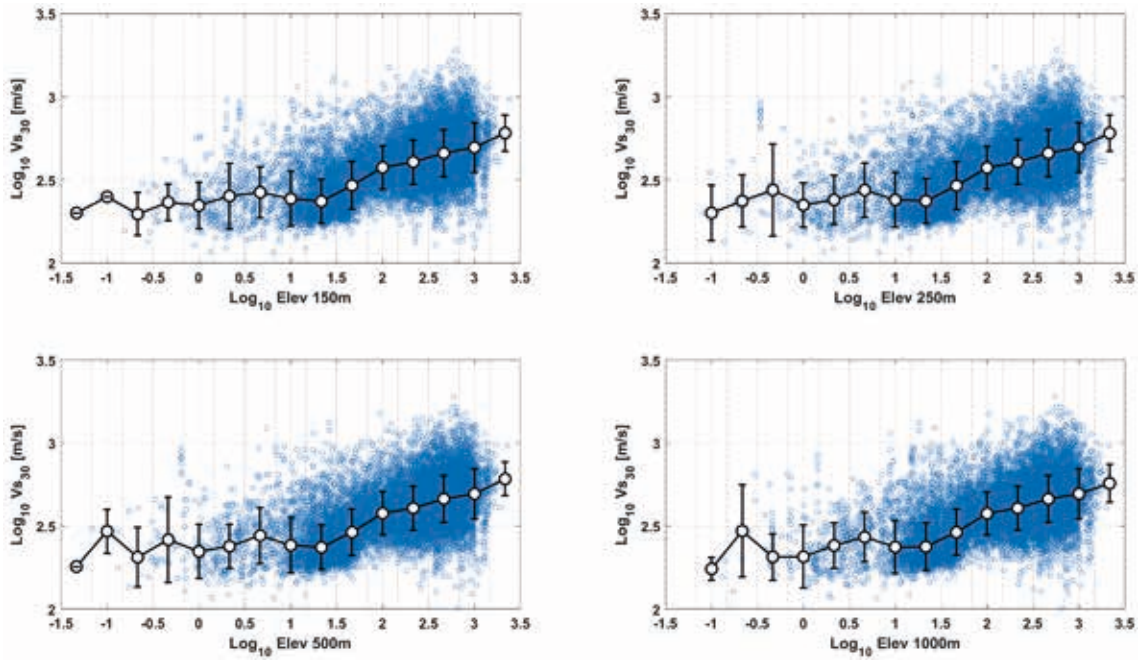


Fig. A12 - Scatter plot between $\log_{10} Vs_{30}$ [m/s] and $\log_{10}(elevation)$. The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

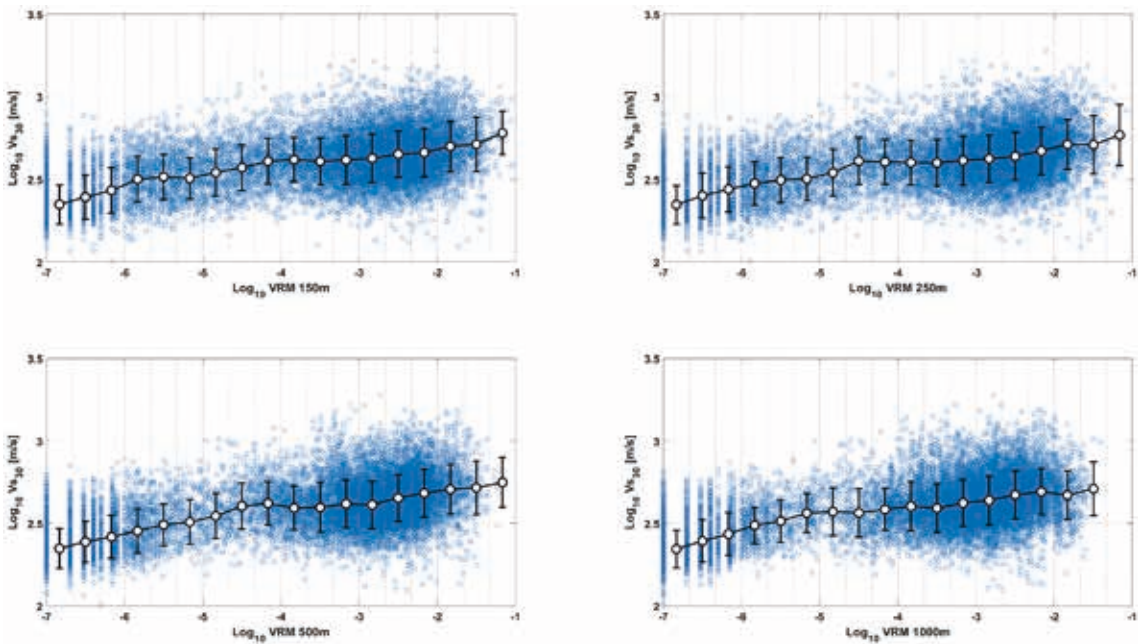


Fig. A13 - Scatter plot between $\log_{10} Vs_{30}$ [m/s] and $\log_{10}(VRM)$. The white markers and error bars indicate the mean and standard deviation within each bin (grey vertical dashed lines).

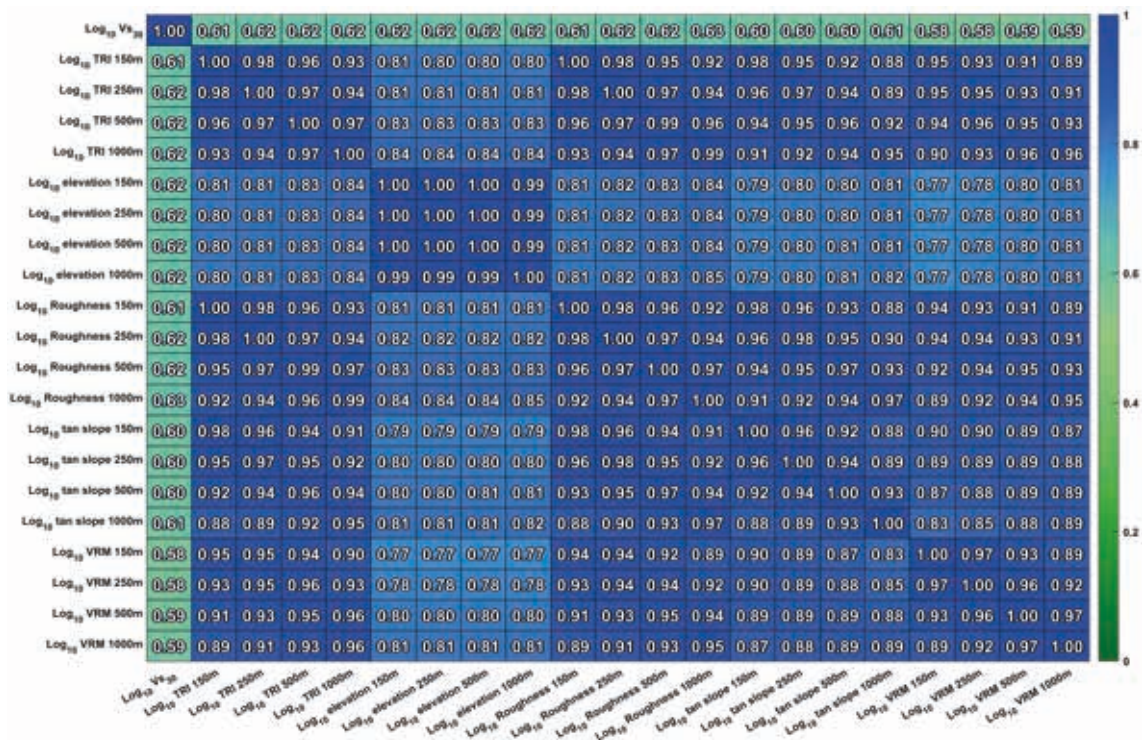


Fig. A14 - Pearson correlation matrix of the selected log₁₀-transformed topographic proxies and log₁₀(Vs30), showing both their correlations with log₁₀(Vs30) and their mutual inter-correlations. Colour intensity represents the magnitude of r (0–1). The first row and the first column indicate the correlation between the log₁₀(Vs30) and each proxy.

Table A1 - List of lithological classes and associated codes as defined in the ISPRA (2021) lithological map.

Lithology	ISPRA lithological code
Limestones	A1
Pelitic-arenaceous complexes	A10
Calcareous-arenaceous complexes	A11
Evaporites	A12
Residual rocks	A13
Cemented debris	A14
Travertines	A15
Dolomites	A2
Marly limestones	A3
Jasper	A4
Quarzarenite	A5
Diatomite	A6
Marls	A7
Conglomerates	A8
Sandstones	A9
Predominantly clayey soils	B1
Predominantly sandy soils	B2

Table A1 - continued.

Lithology	ISPRA lithological code
Predominantly gravelly soils	B3
Mixed-grain soils	B4
Peats	B5
Residual soils	B6
Soils with undefined grain size	B7
Chaotic marine clayey deposits	C1
Marine volcano-sedimentary complexes	C2
Felsic lavas	D1
Intermediate lavas	D2
Mafic lavas	D3
Unknown-composition lavas	D4
Pyroclastics, tuffs, ignimbrites	D5
Pyroclastics + lavas	D6
pedogenised tuffs	D7
Scoriae, lapilli, pumice, bombs	D8
Granitoid rocks	E1
Intermediate plutonic rocks	E2
Foidic plutonic rocks	E3
Phyllites and micaschists	F1
Gneiss	F2
Prasinite	F3
Ophiolites	F4
Serpentinities	F5
Contact metamorphic rocks	G1
Marbles	G2
Metamorphic dolomites	G3
Quartzites	G4
Granulites	G5
Low-grade metamorphic rocks	H1
Mineralisations of particular interest	H2
Waters and glaciers	N1
Anthropic settlements	N2
Landfills	N3

Table A2 - List of lithological classes and associated codes as defined in the lithological map of Italy by Bucci *et al.* (2021, 2022).

Lithology	Bucci <i>et al.</i> (2021, 2022) lithological code
Alluvial and marine deposits	Al
Unconsolidated clastic rocks	Ucr
Carbonate rocks	Cr
Siliciclastic sedimentary rocks	Ssr
Schistose metamorphic rocks	Sr
Consolidated clastic rocks	Ccr
Intrusive rocks	Ir
Non-schistose metamorphic rocks	Nsr
Pyroclastic rocks	Pr
Mixed sedimentary rocks	SM
Glacial drift	Gd
Chaotic - mélange	Cm
Lavas and basalts	Lb
Marlstone	M
Evaporite	E
Lakes and ice	Li
Beach deposits	B
Mass wasting material	Mw
Anthropogenic deposits	Ad