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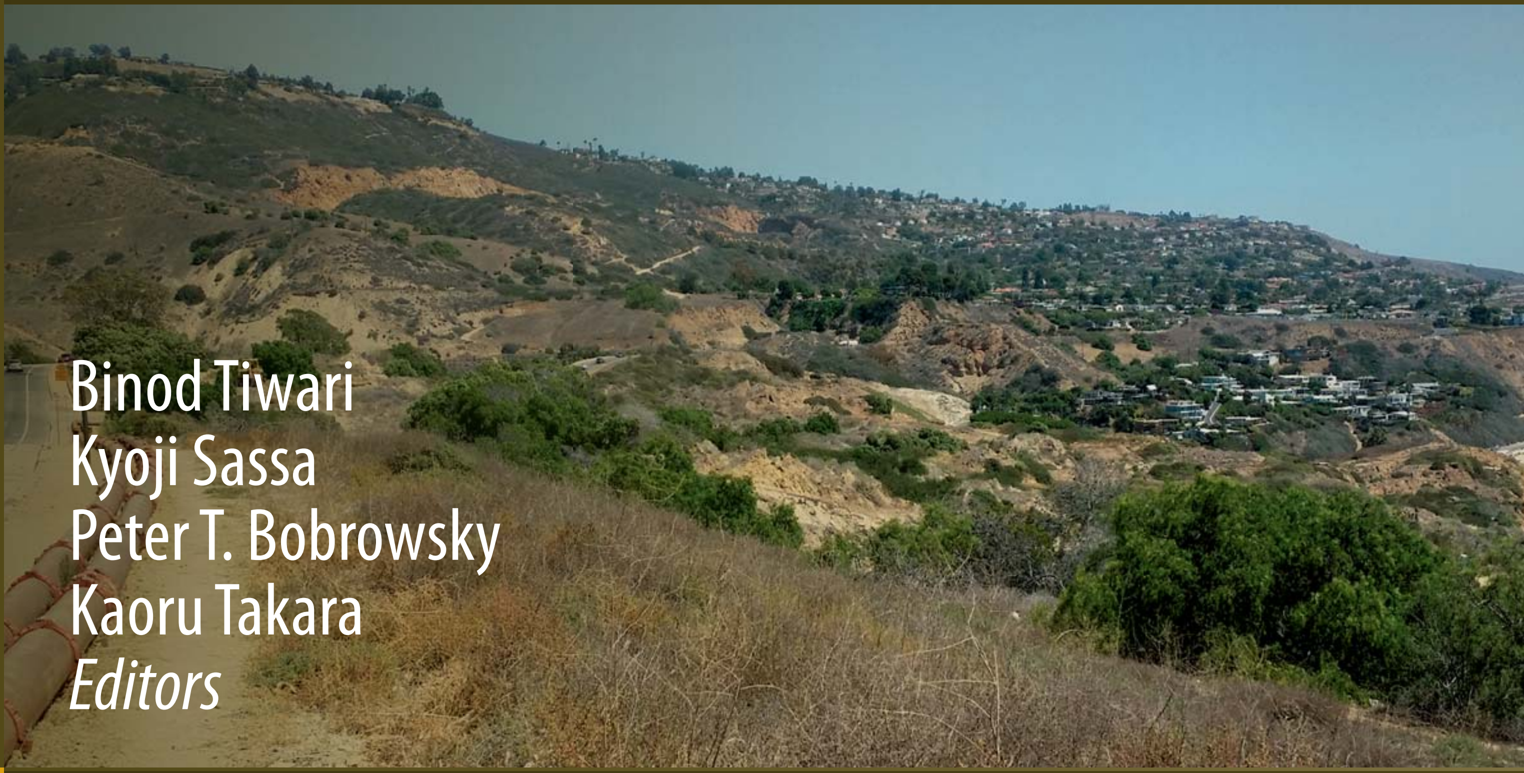

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Analysis of Shear Strength Variability of Ash-Fall Pyroclastic Soils Involved in Flow-Like Landslides

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Abstract

Rainfall-induced shallow landslides of flow-like type are very common in ash-fall pyroclastic soils originated from explosive activity of the Somma-Vesuvius volcano (southern Italy). Over the last few centuries, these phenomena have frequently affected pyroclastic soil-mantled slopes of mountain ranges that surround the volcano causing hundreds of casualties. Many researches have been focused on this topic, especially after the occurrence of the deadly debris flow events of May 1998, which hit Sarno Mountains causing 160 victims. Among the various aspects studied, aimed at the assessment and mapping of hazard to landslide initiation and propagation, the estimation of shear strength of ash-fall pyroclastic soils still deserves to be advanced. This is especially due to the relevant spatial variability of geotechnical properties which are controlled by complex stratigraphic settings. According to such a research focus, the present paper deals with physical and shear strength laboratory characterizations of ash-fall pyroclastic soils and the estimation of the inherent variability. A total number of 97 direct shear tests, supported by grain size and Atterberg's limits analyses, were carried out. The high number of tests allowed to perform a statistical analysis based on quantile regression approach and aimed at considering the uncertainty related to the high variability of Mohr–Coulomb's shear strength parameters. The results obtained show values, especially for the drained friction angle (ϕ′), generally higher than those considered in literature. Outcomes of the study and the approach proposed can be conceived as a benchmark for further analyses aimed at the assessment of hazard to initiation of this type of landslides or related physically-based rainfall thresholds.

Keywords

Ash-fall pyroclastic soils • Shear strength parameters • Variability • Quantile regression analysis

Introduction

Shallow landslides triggered by rainfall events occur worldwide and involve different soil types covering bedrock. The hazard related to the occurrence of such phenomena is generally very high, inducing a high risk condition in areas characterized by an extensive urbanization (Sidle and Ochiai 2006). Significant and world-wide known examples are flow-like mass movements that periodically involve the ash-fall pyroclastic soil mantled slopes of peri-Vesuvian carbonate mountains, such as Sarno-Avella-Salerno and Lattari in Campania Region (southern Italy). As a matter of fact, ash-fall pyroclastic soils mantling these mountain slopes are highly susceptible to landslide onset under prolonged rainfall followed by intense rainstorms (Fiorillo and Wilson 2004; Napolitano et al. 2016).

Different consecutive evolutionary stages characterize these flow-like movements: (1) initial debris slide (soil slip) (Campbell 1974), involving a few tens of cubic meters of ash-fall pyroclastic soils; (2) debris avalanche (Hungr et al.

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2014) that widens the depleted mass and volume along the slope; (3) debris flow (Revellino et al. 2004; Hungr et al. 2014), when the flow-like landslide channelizes into the hydrographic network. The initial debris slide is always present and may evolve directly into a debris flow or into a debris avalanche only.

The most recent and deadly events occurred in May 1998 along slopes of Sarno Mountains caused 159 casualties and damaged severely four towns (Bracigliano, Quindici, Sarno and Siano) located at the footslope of Mount Pizzo d'Alvano (Bilotta et al. 2005).

Several factors related to local surficial geology, geomorphology, hydrology and topography have been considered as fundamental in controlling hazard to the initiation this type of mass movements. Among these factors, also geotechnical properties of ash-fall pyroclastic soils were recognized as very relevant. Therefore, several studies tackled with this topic trying to manage complex stratigraphic settings and spatial variability of geotechnical properties (Cascini et al. 2005; De Vita et al. 2013).

In such a scientific framework, the present study is focused on the assessment of shear strength of ash-fall pyroclastic soils covering Sarno Mountains by a high number of laboratory tests to consider statistically the inherent variability. In fact, due to the high grain size heterogeneity as well the low stress condition, related to the shallow depth, the estimation of shear strength in these soils is often challenging as well as unclear the interpretations of results of laboratory tests. To consider the uncertainty related to results of direct shear tests, a quantile regression analysis was carried out for the shallower soil horizon, which is the most involved in the initial failure. The proposed approach and the results obtained advance the characterization of shear strength of ash-fall pyroclastic soils, representing potentially a benchmark for the setting of distributed landslide hazard and stability models or physically-based rainfall thresholds.

Geological Setting

Sarno, together with Lattari, Avella and Salerno Mountains, belong to the westernmost sector of the Apennines Chain and face at a short distance (10–20 km) the Somma-Vesuvius volcano. These mountain ranges are formed by Mesozoic carbonate platform series which were thrust during the Miocene compressive tectonic events over the external palaeogeographical units. Subsequently they were faulted during the Quaternary by extensional tectonic phases (Vitale and Ciarcia 2018). During Quaternary, ash-fall pyroclastic deposits derived by the explosive volcanic activity of Somma-Vesuvius and Phlegrean Fields volcanoes covered discontinuously these mountain ranges (Rolandi et al. 1998, 2000). The older volcanic deposits, mainly represented by ash-flow deposits of Ignimbrite, pumices and ashes, erupted by the Phlegrean Field volcanoes (39 k-years), form the "Ancient Pyroclastic Complex" (APC), while the younger products, mainly associated to Somma-Vesuvius explosive activity, form the "Recent Pyroclastic Complex" (RPC) (Rolandi et al. 2000).

The most important eruptions associated with RPC are: Codola eruption, 25 k-years B.P. (Rolandi et al. 2000); Sarno eruption, 17 k-years B.P. (Rolandi et al. 2000); Ottaviano eruption, 8.0 k-years B.P. (Rolandi et al. 1993a); Avellino eruption, 3.6 k-years (Rolandi et al. 1993b); Pompei eruption, A.D. 79 (Lirer et al. 1973); A.D. 472 (Rolandi et al. 1998) and A.D. 1631 eruption (Rosi et al. 1993). Along slopes, complete volcaniclastic series were observed in the most conservative area only, which are characterized by slope angle values lower than 30°, while elsewhere they appear incomplete due to the action of the denudational processes. Due to this phenomenon, thicknesses of the ash-fall pyroclastic soil mantle range from maximum values, varying from 7 to 4 m in the slope angle range lower than 30°, to zero for slope angle values greater than 50° (De Vita et al. 2006a, 2013).

Volcaniclastic series along slopes have a greater complexity due to the alternation of unweathered ash-fall soil and pedogenized horizons (paleosols). In particular, considering the principal pedogenetic soil horizons (USDA 2014), lithostratigraphic features and USCS soil classification system, a typical stratigraphic setting can be recognized (De Vita et al. 2006b) as formed by: (1) A soil horizon, consisting of abundant humus (Pt); (2) B soil horizon, mainly characterised by pumiceous clasts highly subjected to pedogenetic processes (SM); (3) C soil horizon, formed by pumiceous pyroclasts, weakly weathered (GW or GP); (4) Bb horizon, corresponding to a B horizon buried by a successive depositional event and thus considerable as a paleosol (SM); (5) Cb soil horizon, representative of a buried C horizon (GW or GP); (6) Bb_{basal} soil horizon, corresponding to a residual pyroclastic deposit, highly weathered by pedogenesis (SM); (7) R horizon, consisting of fractured carbonate bedrock with open joints filled by the overlying paleosol, for the first few meters and below by air.

Data and Methods

Undisturbed and disturbed soil samples were taken at different depths in exploratory trenches, dug at the top of main scarps of four landslides (F1, F2, F3 and F4) triggered on May 1998 (Fig. 1). In particular, two sets of samples were collected for geotechnical characterizations at different depth ranges: 17 samples were taken from 1.10 to 1.30 m (B soil horizon); 18 samples were collected from 2.00 to 2.50 m

(C–Bb soil horizons). Undisturbed sampling was carried out by pushing into the soil surface cubical steel boxes (12 cm side) with an open face and a basal cutting edge. Stratigraphic setting observed in the exploratory trenches (Fig. 1) confirmed the existence of a volcaniclastic series corresponding to that described in previous studies (De Vita et al. 2006b, 2013).

Geotechnical index properties were determined by means of standard laboratory procedures: specific gravity of solid particles (G_s) (ASTM D854), grain size analysis by means of both sieving and sedimentation methods (ASTM D421 and ASTM D422), Atterberg's limits (w_L and w_P) and Plasticity Index ($\mathrm{PI} = w_L - w_P$) (ASTM D4318). Porosity (n) and void ratio (e) were also estimated. 97 standard direct shear tests (ASTM D3080) were carried out to estimate the drained Mohr–Coulomb's shear strength parameters, c' and ϕ'. All shear tests were performed on standard specimens with dimensions of 60 × 60 × 24 mm. Values of drained normal stress (σ') were set around that estimated at the depth of sampling and considering variations corresponding to depth steps of 0.20 m. Due to grain size heterogeneity affecting the same soil horizon, and specifically for the occurrence of a small fraction of lapilli found both in the B and Bb soil horizons, tangential stress (τ) values at the failure resulted significantly variable for the same σ' interval. Dilatancy effects and crushing of coarse lapilli pyroclasts were recognized as mainly controlling this variability and therefore values of drained friction angle (ϕ') and intercept drained cohesion (c').

To consider uncertainty related to high spatial variability of shear strength and generalize results derived by sampling in different areas, results of laboratory tests were aggregated for the same soil horizon and analysed by a quantile regression approach.

Finally, a comparison of results obtained with those proposed in literature by various authors (Crosta and Dal Negro 2003; Bilotta et al. 2005; Cascini et al. 2005; De Vita et al. 2013) for ash-fall pyroclastic of Sarno Mountains was carried out.

Results

Results of grain size analysis, by wet sieving standard procedures of American Society for Testing and Materials and consistency limits are shown in Fig. 2. The grain size curves present a significant variability for each soil horizon due to heterogeneity of the analysed samples, even if belonging to the same soil horizon. In general, considering all samples, the gravel fraction ranges from 8.8 to 79.6%, sand fraction from 20.4 to 69.4%, silt fraction from 0.0 to 32.2% and clay fraction from 0.0% to 3.0%. These results confirmed the negligible presence of clay fraction which, accounting also for results of consistency limits (Fig. 2), allowed to consider these soils as non-plastic. Moreover, by USCS—Unified Soil Classification System (Stevens 1982), sampled soils were classified as Silty Sand (SM), for B and Bb soil horizons, and as Gravel with Sand, from well graded (GW) to poor graded (GP), for lapilli C soil horizons.

Considering field recognitions about the prevailing involvement of B soil horizon in the development of the landslide surface of rupture, as well as the feasibility of undisturbed sampling, the most part of samples were collected for B and Bb soil horizons. While only disturbed

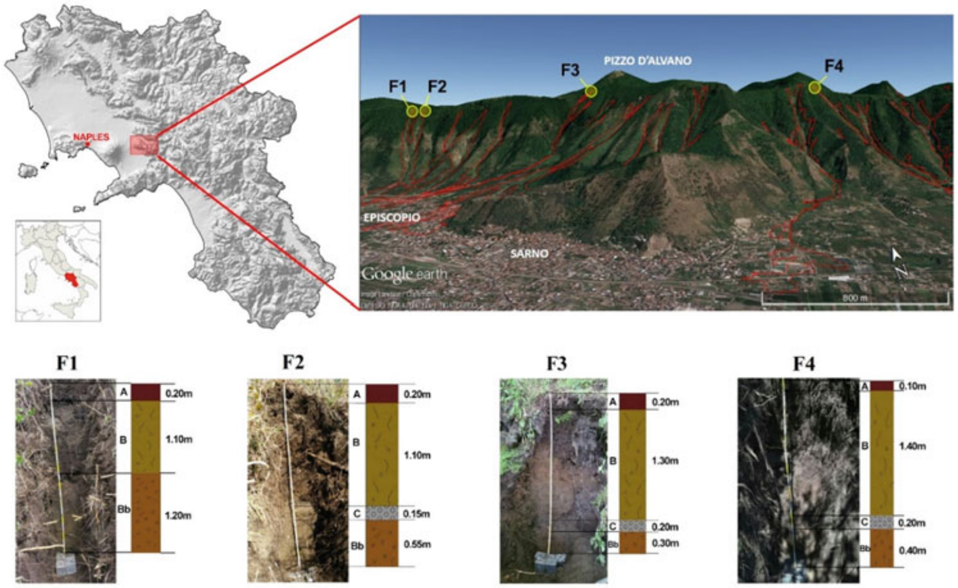


Fig. 1 Study area: location of landslides F1, F2, F3 and F4 and photographs of exploratory trenches

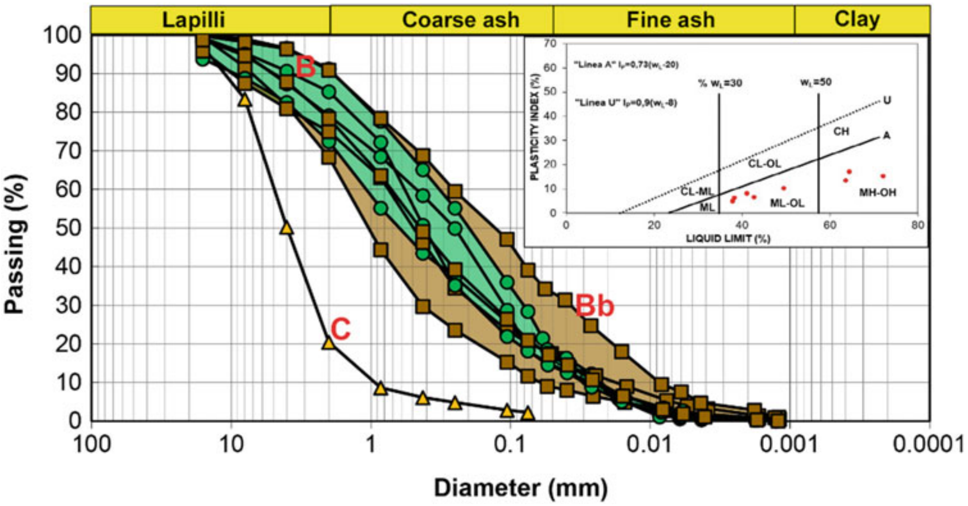


Fig. 2 Grain size and consistency limits of volcaniclastic soil horizons (B, C and Bb horizon) sampled at landslides F1, F2, F3 and F4

samples were collected for lapilli C horizon. Consequently, τ-σ′ plots to estimate Mohr–Coulomb envelopes, for B and Bb soil horizons, were based on a high number of data, much greater than three, as it is recommended at least by standard procedure. Result values of σ′ and τ data obtained for each soil horizons of each landslide were aggregated to perform different linear regression analyses, thus allowing to assess variability of c′ and ϕ' (Table 1). Due to extreme cohesionless of lapilli soil horizon, direct shear tests were carried out on disturbed samples only, which were reconstituted in laboratory at the same value of void ratio as estimated in the other experimental field and laboratory determinations (De Vita et al. 2013).

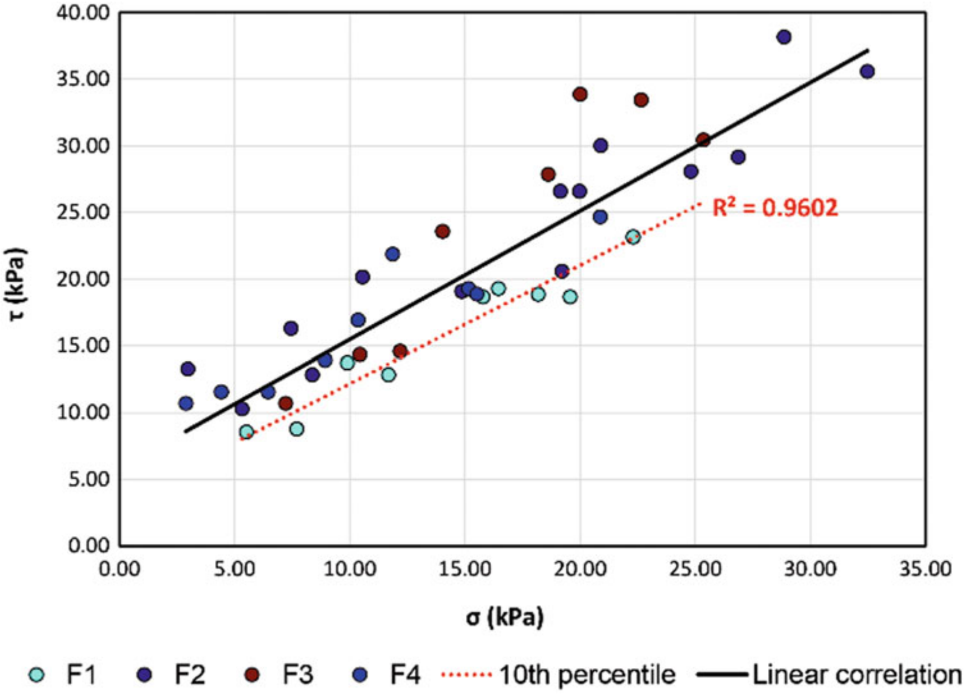
The results obtained show values of ϕ' ranging from 38.5° to 53.6°, for B horizon, and from 31.0° to 61.2° for Bb soil horizon. In some cases, results appear very high due to the presence of coarse lapilli pumiceous pyroclasts, which caused crushing and dilatancy phenomena. To confirm such a finding, a consistent linear empirical relationship (R^2 = 0.7511) was found between drained friction angle (ϕ') and the sum of gravel and sand grain size fractions, which showed a control of grain size on shear strength. A unique value of 70.1° was estimated for reconstituted samples of lapilli C soil horizon. This very high value was interpreted as being related to dilatancy effect due to both coarse grain sizes and low stress levels considered in testing.

Drained cohesion (c′) was found ranging from 1.47 to 8.14 kPa for B soil horizon, and from 5.39 to 9.61 kPa for Bb soil horizon. Due to the general cohesionless behaviour of these soil horizons, the not negligible values of c′ were attributed to both reinforcement of root apparatuses and effect of crushing of lapilli pumiceous pyroclasts. Instead, a very high value of 32.75 kPa was found for the drained cohesion (c′) of the lapilli C soil horizon. This result, apparently very anomalous for a typical cohesionless soil, was understood as due to the effect of intercept (apparent) cohesion, caused by the crushing of lapilli pumiceous pyroclasts and favoured by the interlocking and angular shape of grains (Mitchell and Soga 2005). Due to the limited number of direct shear tests carried out on C soil horizon as well as the effect of scale factor related to the limited dimensions of the shear box in comparison to grain sizes, results obtained were considered with a lower reliability and not useful for any slope stability calculations.

Table 1 Values of Mohr–Coulomb's shear strength parameters obtained by unique regression analyses carried out on results obtained by N tests for samples taken in landslide crowns of four landslides (F1, F2, F3 and F4) and different soil horizons (B, C and Bb). The sample ID is made by joining the landslide and soil horizon identifications. Depth of sampling is also shown

ID	Depth (m)	N	c′ (kPa)	ϕ′ (°)
F_1–B	1.30	9	3.63	40.70
F_2–B	1.20	14	8.14	41.18
F_3–B	1.30	10	1.47	53.61
F_4–B	1.10	11	8.04	38.49
F_2–C	1.30	9	32.75	70.12
F_1–B_b	2.50	12	6.67	61.23
F_2–B_b	2.00	11	5.39	56.30
F_3–B_b	2.00	9	8.43	31.02
F_4–B_b	2.10	12	9.61	49.02

Fig. 3 Results of directs shear tests carried out on B horizon for F1, F2, F3 and F4 landslides. The continuous black line indicates the unique linear correlation related to all data, while the dotted red line shows quantile regression analysis (10th percentiles)



However, due to the wide range of variability of shear strength parameters, a quantile regression analysis was attempted to elaborate results of 44 direct shear tests obtained for B soil horizon. The latter is the most involved in initial landslides phenomena and therefore is considered as the most representative in this study.

In particular, a quantile regression analysis was carried out considering the 10th percentile (Fig. 3). Such a low percentile value was conceived as representative of lower values of shear strength occurring in zones with finer grain sizes, thus to take into account spatial variability of shear strength by a conservative approach. The results obtained show values of drained friction angle ϕ'_{10th} = 41.5° and drained cohesion c'_{10th} = 3.24 kPa.

Finally, a comparison with results of Mohr–Coulomb's shear strength parameters known in literature (Crosta and Dal Negro 2003; Bilotta et al. 2005; Cascini et al. 2005; De Vita et al. 2013) was performed (Table 2). Values of drained friction angle (ϕ′) related to B, C and Bb soil horizons, resulted always the highest, except for the case of Crosta and Dal Negro (2003) and particularly for the soil horizon that Authors identified as characterized by clay accumulation (B_t) and with little or no apparent illuvial accumulation of materials (B_w). In these cases, Crosta and Dal Negro (2003) indicated a range of drained friction angle (ϕ′) that in both cases includes the experimental values obtained in this research for the B soil horizon by quantile regression analysis at the 10th percentiles. Differently, drained cohesion (c′)

Table 2 Comparison between Mohr–Coulomb's shear strength parameters estimated in this study (for B horizon—quantile regression at the 10th percentile) and literature data. De Vita et al. (2013) considered c'_{10th} and ϕ'_{50th}. Class "A" in Bilotta et al. (2005) and Cascini et al. (2005) means ashy soils with a finer grain size distribution, while class "B" ashy soils with higher porosity values and lower specific gravity. In Crosta and Dal Negro (2003), B_b stands for buried horizons, B_t for clay accumulation and B_w for little or no apparent illuvial accumulation of materials

	Horizon	c′ (kPa)	ϕ′ (°)
This research	$B_{10th\ perc}$	3.33	41.5
	C	32.75	70.1
	Bb	7.65	49.4
De Vita et al. (2013)	B	5.00	32.0
	C	0.00	37.0
	Bb	3.43	34.0
Bilotta et al. (2005)	Class "A"	<2.94	30.0–35.0
	Class "B"	<2.94	36.0–41.0
Cascini et al. (2005)	Class "A"	4.90–15.00	32.0–35.0
	Class "B"	0.00–4.90	36.0–41.0
Crosta and Dal Negro (2003)	B_b	34.02	38.5
	B_t	0.00–15.00	37.8–44.9
	B_w	10.00–18.34	35.5–45.9

values resulted by this research match better with values known in literature (Table 2).

Conclusion

Physical and shear strength characterizations of ash-fall soils involved in rainfall-triggered shallow landslides represent a crucial aspect for advancing the assessment of hazard to slope instability initiation. Several attempts were made in literature to estimate reference values for Mohr–Coulomb's shear strength parameters even if results obtained up to now appear affected by a high variability due soil heterogeneity and difficult sampling. According to such a focus, this research is aimed at advancing the characterization of shear strength for these soils also considering the inherent variability related to grain size heterogeneity of the same soil horizon. Preliminary results of direct shear tests have highlighted a relevant variability, confirming the complex behaviour of these soils. In this research a quantile regression analysis is proposed as a possible approach to manage variability of shear strength by a conservative approach. The obtained results can be considered consistent due to the high number of data and potentially advancing the assessment of hazard to landslide initiation by slope stability distributed modelling or the assessment of physically-based rainfall thresholds.

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