Characterization of Hillslope Deposits for Physically-Based Landslide Forecasting Models

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Abstract

Physically-based models employed for landslide forecasting are extremely sensitive to the use of geological information and a standard, universally accepted method to input maps containing information of geological interest into the models still has never been established. In this study, we used the information contained in a geo-database aimed to characterize the geotechnical and hydrological parameters of the hillslopes deposits in Tuscany, to find out how to organize and group the measurements to spatially create classes that mirror the distribution of the various types of bedrock lithology. Despite the deposits analysed are mainly consisting of well sorted silty sands, statistical analyses carried out on geotechnical and hydrological parameters highlighted that it is not possible to define a typical range of values with relation to the main mapped lithologies, because soil characteristics are not simply dependent on the bedrock typology from which the deposits originated. Instead, the analysis of the relationship of soil parameters with morphometric parameters (slope angle, profile curvature, planar curvature) shows that the highest correlation between the soil grain size class type (USCS classification) and morphometric attributes is with slope curvature, both profile and planar.

Keywords

Soil geotechnics • Physically based modelling • Landslides • Tuscany

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Introduction

Many kinds of physically-based landslide prediction models for rainfall-triggered shallow landslides have been presented in the literature so far (Pack et al. 2001; Baum et al. 2002, 2010; Rosso et al. 2006; Simoni et al. 2008; Ren et al. 2010; Arnone et al. 2011; Mercogliano et al. 2013; Rossi et al. 2013; Alvioli and Baum 2016; Salciarini et al. 2017).

One of the most important factors that influences the prediction accuracy and the sensitivity of the physically-based model is the availability of detailed databases of physical and mechanical properties of rocks and soils in the selected study areas. Geotechnical and hydrological variables are often difficult to manage, and their measurement is difficult, time-consuming and expensive, especially when working on large, geologically complex areas (e.g. Baroni et al. 2010; Park et al. 2013; Tofani et al. 2017).

In addition, a poor understanding in the of the geotechnical and hydrological input parameters with respect to their spatial organization may endanger the potential application of numerical models over large areas (e.g. Tofani et al. 2017; Salvatici et al. 2018).

Data to be inputted and to feed the physically-based models can be prepared by using different strategies:

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(1) the adoption, for each parameter, of a unique constant value for the whole study area as retrieved from experimental data or derived from literature data (e.g. Jia et al. 2012; Peres and Cancelliere 2014), (2) the use of constant values for the parameters for distinct geological, lithological or lithotecnical units, as derived from direct measurements (Segoni et al. 2009; Baum et al. 2010; Montrasio et al. 2011; Zizioli et al. 2013; Bicocchi et al. 2016; Tofani et al. 2017) or from existing databases and published data (Ren et al. 2014; Tao and Barros 2014), or (3) the definition of selected parameters, such as the cohesion and friction angle values, as random variables using a probabilistic or stochastic approach (e.g. Park et al. 2013; Chen and Zhang 2014; Raia et al. 2014; Fanelli et al. 2016; Salciarini et al. 2017).

In this work we discuss how to deal with the geotechnical and hydrological input data in regional physically-based models. In particular, we want to find an optimal way (1) to determine the ranges of variation and the characteristics of frequency distributions of the geotechnical and hydrogeological parameters that control shallow landslide triggering mechanisms, and (2) to describe the spatial variation in the geotechnical and hydrological data in relation to the information contained in the geological maps and to the physical factors such as morphometric attributes. The area of application of this approach is Tuscany region, where more than one hundred survey points of the geotechnical and hydrological parameters measurements are available (Bicocchi et al. 2019).

Geographical and Geological Description of the Study Area

Tuscany region (Fig. 1) is a topographically complex region located in central Italy strongly affected by shallow landslides occurring after major meteorological events (Giannecchini et al. 2007; Mercogliano et al. 2013; Tofani et al. 2017). The highest ridges are in the northern and eastern portion of the region. The northwestern part is characterized by mountains comprised of metamorphic rocks (i.e. Apuan Alps) and by steep valleys with thick colluvial and alluvial deposits, while the eastern part is characterized by mountains mainly formed by sedimentary rocks and by intermountain basins filled with alluvial deposits. These mountains belong to the Northern Apennine, a NE-verging fold-and-thrust orogenic belt originated from the closure of the Jurassic “Ligure-Piemontese” Ocean and the subsequent Oligocene–Miocene collision between the continental Corso-Sardinian block and the Adria microplate (e.g., Boccaletti and Guazzone 1974). The central and southern parts are characterized by hilly morphology with an isolated volcanic relief and flat plains or wide valley floors where the main rivers flow.

A lithological map of the bedrock for Tuscany was prepared (Fig. 1) by customizing that lithological map previously derived from the geological map of Italy, 1:500,000 by ISPRA (Italian National Institute for Environmental Protection and Research). The bedrock, relative to its areal distribution in the hilly and mountainous part of the region, is mainly represented by of arenaceous, calcareous and pelitic flysch units.

Geotechnical and Hydrological Measurements

The data analysed are represented by samples collected at 102 different sites (Bicocchi et al. 2019; Fig. 1). The geotechnical and hydrological parameters for characterizing the soils were determined as described in Tofani et al. 2017 and Bicocchi et al. 2019. In particular, the Borehole Shear Test (BST; Luttenegger and Hallberg 1981) for measuring the soil shear strength parameters, a constant head permeameter test performed with the Amoozemeter instrument (Amoozegar 1989) and matric suction measurements with a tensiometer, were used for the in-situ determinations. In addition, laboratory tests were conducted at the Department of Earth Sciences, University of Florence, to determinate grain size distributions, Atterberg limits, soil phase relationships (bulk porosity n; saturated, natural and dry unit weight, γ_{sat}, γ and γ_d, respectively) and the soil organic matter contents (SOM; for the latter refer to Masi et al. 2020 for further information about the analysis methods adopted).

Results

The analysed deposits are mostly classified as well-sorted silty—clayey sands, i.e. SW, SM, SC and SM-SC classes by using the Unified Soil Classification System (USCS; Wagner 1957). Nevertheless, a non-negligible part of the samples is characterized by higher contents of silt and clay (ML and MH class in the USCS), whilst an isolated sample is classified as GW (Fig. 2).

Descriptive statistics concerning dry unit weight, bulk porosity, internal effective friction angle and saturated hydraulic conductivity values are reported in Table 1. The dry unit weight (γ_d) ranges between 10.7 and 20.8 kN m^{-3}, with a mean value of 15.5 kN m^{-3}. Internal effective friction angle values (φ') vary from 15° to 45° with an average value of 32°, but much part of the value lies in a narrower interval (±5° from the arithmetic mean). The bulk porosity

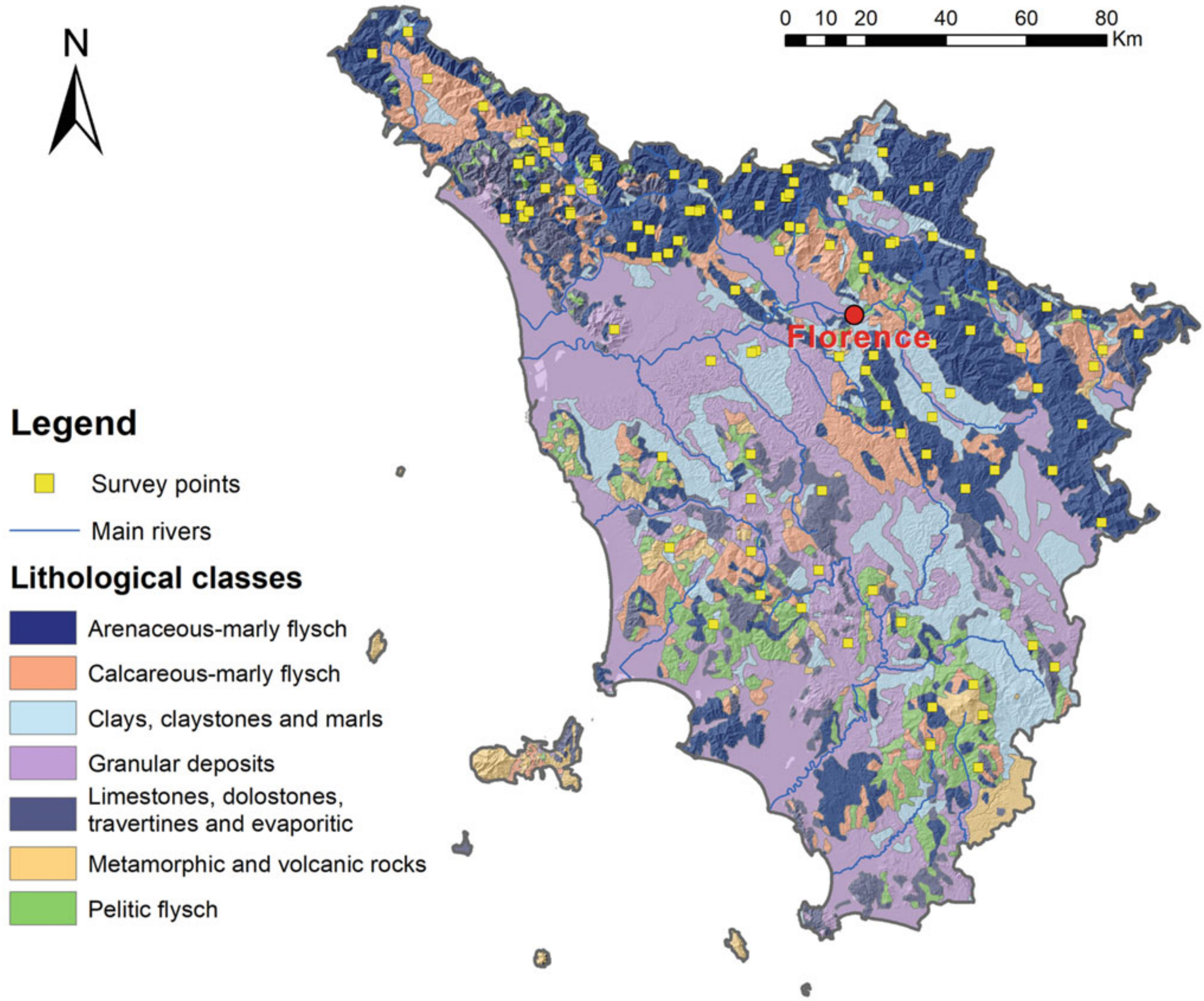

Fig. 1 Lithological map of Tuscany (bedrock) and location of the survey points (from Bicocchi et al. 2019)

(n) values span a wide interval: from 19.9 to 58.8% with a median value of 38.8%. Also, the values of k_s range in a wide interval from 4 10^{-8} to 8 10^{-5} m s^{-1}. The standard deviation (σ) values stress out this aspect since σ is $\sim$15% of the arithmetic mean value for φ' and γ_d, while is much higher for n and k_s.

The main mineral phases detected in the samples of the 27 selected sites, representative of the different USCS soil types and bedrock lithology, are mica, quartz, non-swelling clay minerals, plagioclases, k-feldspar and calcite. The SOM normalized to the bulk samples ranges between 1.8 and 8.9% by weight, the highest values of the SOM content being associated with forest and woodlands without shrubs. The SOM values distribution showed close relationships with the abundance of the inorganic finer fractions (silt and clay) of the soil samples (Masi et al. 2020).

Discussion

In order to define a proper way to spatialize the parameters to be used for physically-based forecasting models some further analyses are carried out to examine the relationship between (1) soil parameters and bedrock lithology and (2) soil parameters and morphometric attributes.

Aggregated Data Statistics: Grouping by Bedrock Lithology Versus by USCS Classification

First of all, we studied the distribution of the soils (Table 2), classified according to USCS, with respect to the underlying bedrock types recognized in the map (Fig. 1). Arenaceous marly flysch (AMF), calcareous marly flysch (CMF),

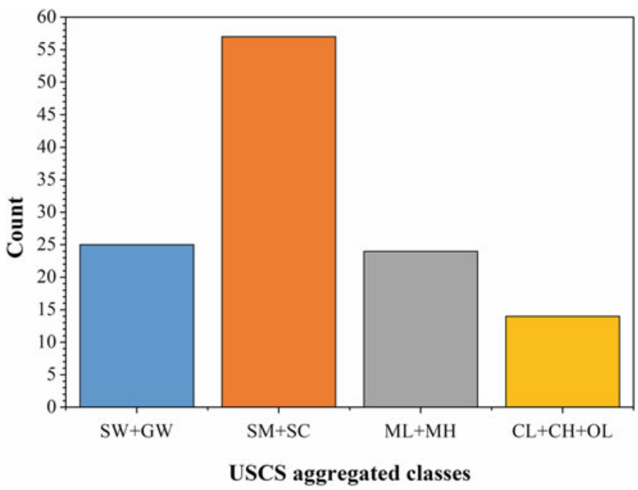

Fig. 2 Distribution of USCS aggregated classes for the samples from Bicocchi et al. (2019)

Table 1 Descriptive statistics of selected geotechnical parameters

	γ_d (kN m^{-3})	ϕ' (°)	n (%)	k_s (m s^{-1})
N° of measurements	81	109	81	119
Min	10.7	15	19.9	4.E−08
Max	20.8	45	58.8	8.E−05
Arithmetic mean	15.5	32	40.2	3.E−06
Median	15.9	32	38.8	1.E−06
Std. dev. (σ)	2.2	5	9.5	9.E−06

Table 2 Soil classification of the bedrock lithologies according to USCS classification. N°: number of survey points. AMF: arenaceous marly flysch, CMF: calcareous marly flysch, LDTE: limestones, dolomites, travertines and evaporitic deposits, PF: pelitic flysch, CCM: Clay, claystone and marls, GD: granular deposits, MVR: Metamorphic and volcanic rocks

Bed-rock	N°	SW + GW	SM + SC	ML + MH	CL + CH + OL
AMF	57	18	27	9	3
CMF	21	0	11	5	5
CCM	9	0	3	4	2
GD	11	1	3	4	3
LDTE	11	2	6	2	1
MVR	3	2	1	0	0
PF	8	1	5	2	0

limestones, dolomites, travertines and evaporitic deposits (LDTE), and pelitic flysch (PF) have mainly silty sands and clayey sands soil deposits. Clay, claystone and marls (CCM) and granular deposits (GD) show silty soils with low and high plasticity. As MVR class consists only of, three observations, every consideration is statistically poorly significant.

The variability of the main parameters (φ', γ_d and k_s), which play key roles in triggering slopes instability, was further investigated aggregating these parameter values according to the pertaining bedrock lithological and the USCS classes (Fig. 3).

Aggregation based on USCS classes show friction angle values distribution quite symmetric, especially for SM-SC and SW classes, although the range of the values covers over 20°. Conversely, the ML + MH box plot is asymmetric, because of the short distances between the box upper limit and the maximum values, while the distance between the lower limit and minimum values is quite high (over 10°). Dry unit weight box plots are symmetric in their shape, apart from SW and secondarily for CL + CH + OL, but the values are extremely dispersed. Eventually, k_s values, as for the data aggregated by bedrock class, were log-transformed prior to making up the box plots. The conductivity values are asymmetrically distributed with respect to the arithmetic mean values, which are located far above the median and often above the 3rd quartile (i.e. the upper box limits).

The aggregation based on bedrock lithology shows boxes of effective friction angle quite symmetric, as the median is very similar to the arithmetic mean. The dry unit weight box plots are symmetric in their shape, apart for the granular deposits (GD) and limestones, dolomites, travertines and evaporitic deposits (LDTE) classes, with median and arithmetic mean values very close and the space between the quartiles homogeneously distributed. Once again, hydraulic conductivity values show some distinctive asymmetric distribution with respect to the arithmetic mean values, which are located far above the median and often above the 3rd quartile.

An interesting fact to note is that, in the study area, a reliable extrapolation of soil parameters is quite difficult to achieve based on the simple observation of the underneath bedrock lithology (Bicocchi et al. 2019). Despite most of the samples in this study being classified as arenaceous marly flysch (AMF), important differences have been found concerning their grain size distribution (Table 2). The main reasons for such decoupling between the bedrock type and the deposit granulometry could be that (Bicocchi et al. 2019): (1) the deposits may have originated from a different bedrock with respect to what they overlie at present, and especially

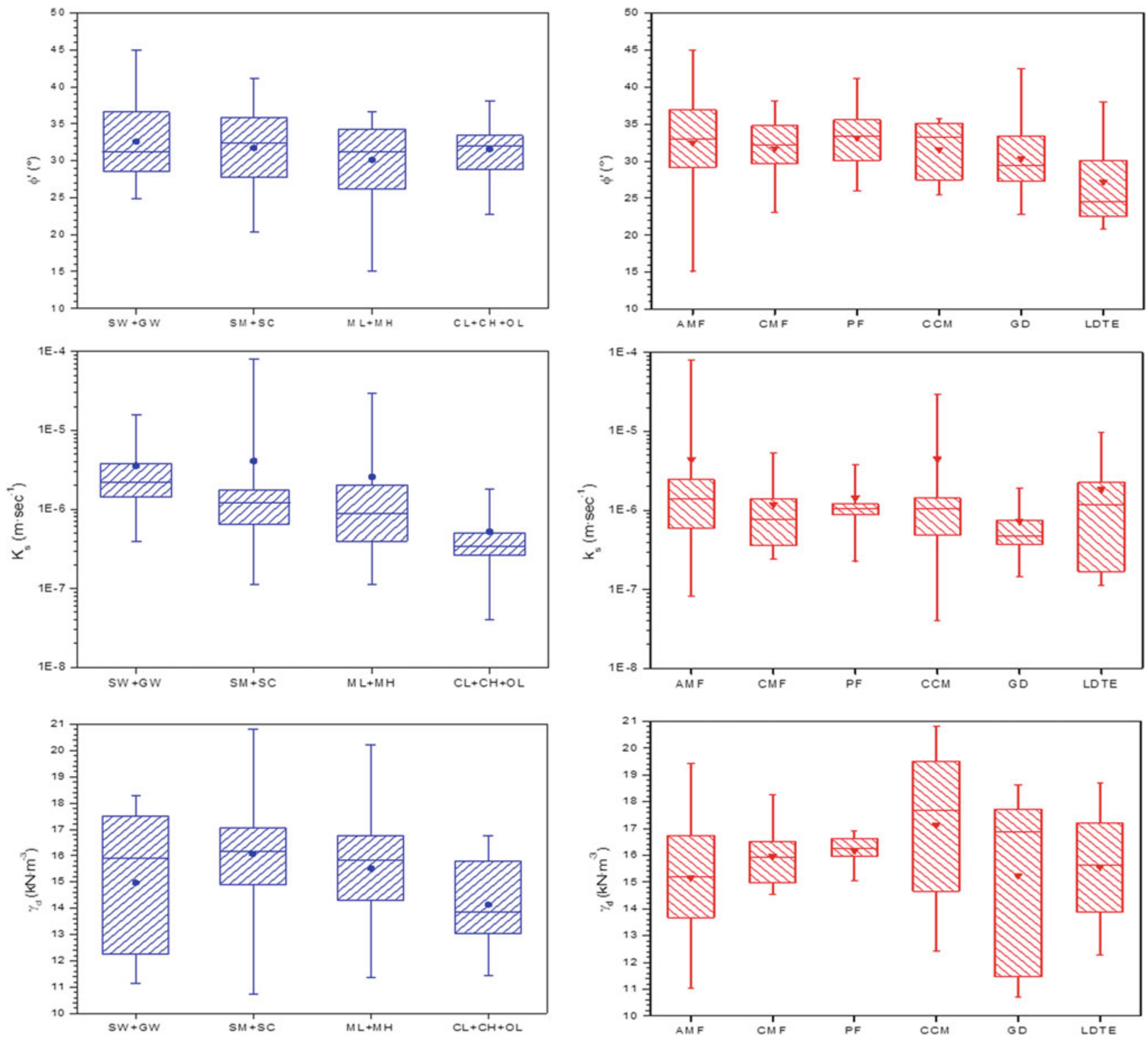

Fig. 3 Box plots of φ' (internal effective friction angle), γ_d (dry unit weight), KS (saturated hydraulic conductivity, scale is logarithmic) for different bedrock lithologies (red coloured, on the right; the dots represents the arithmetic mean value) and for USCS classes (blue coloured, on the left; the dots represents the arithmetic mean value); refer to the text for the bedrock acronyms (modified after Bicocchi et al. 2019)

(2) most of the geological units of the Northern Apennine are quite heterogeneous and intrinsically complex flysch (e.g., Martini and Vai 2001), often characterized by repeated lithological changes (e.g. sandstone to claystone and/or to limestone) in a few tens of meters, so that the characteristics of the regolith, from which the deposits formed, may vary as the bedrock lithological changes occurs.

Compared to the analysis performed by aggregating the values by bedrock lithology, the use of USCS classes, especially looking at SW + GW and CL + CH + OL for the ϕ' and k_s, appears to be more suitable for producing a symmetric distribution and a homogeneous division of the values, while both approaches substantially fail in finding an appropriate way to describe the distribution of dry unit weight box plots.

USCS Soil Type Occurrence Versus Morphometric Attributes

We have investigated the relationship between the soil type, in terms of USCS classification, and morphometric attributes with reference to slope gradient, profile curvature and planar curvature (Fig. 4).

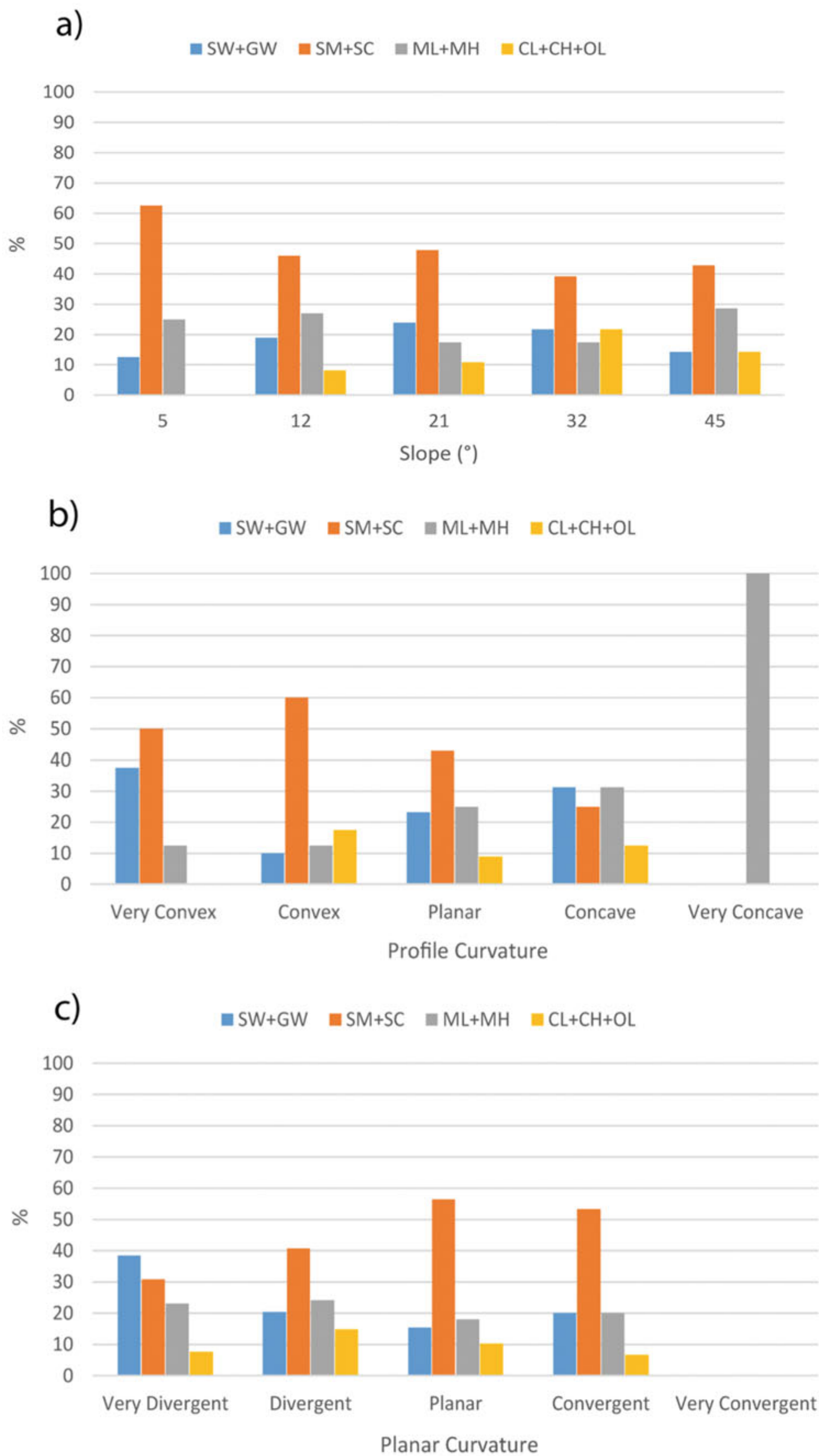

Fig. 4 Occurrence of USCS aggregated soil types with respect to the **a** slope, **b** profile curvature, **c** planar curvature in the hillslopes surveyed (modified after Bicocchi et al. 2019)

In general, at low slope angles, granular soils (SW + GW, SM + SC) are predomisnant, while with the increase of slope angle, the presence of cohesive soils (ML + MH, CL + CH + OL) increases proportionally. This behaviour can be related to the predominance of cohesive forces with respect to frictional ones from low to high slope gradients.

Owing to the profile curvature, it is worth mentioning that in convex areas granular soils (SW + GW, SM + SC) are prevalent while in concave areas the distribution of soil classes is more heterogeneous, and all the soil classes are about evenly represented. This result can be explained considering that in convex areas fine materials are more easily remodeled and transported due to various processes of surface runoff, such as rainwash and sheetwash.

The distribution of soil classes for planar curvature shows that in very divergent areas (crests) coarse granular soils (SW + GW) prevail over fine granular (SM + SC) and cohesive ones (ML + MH, CL + CH + OL). This is in line with the results coming from the profile curvature: in convex and divergent areas, rainwash and sheetwash processes produce residual soils composed of mainly coarse material. In the other classes of planar curvature, silty sands prevail. Nothing can be said about very convergent areas, where no samples have been collected in the analysed database since they usually represent incised channel bottoms or stream thalwegs.

Conclusion

In this work selected information contained in the database of geotechnical (internal effective friction angle, dry unit weight, porosity) and hydrological (saturated hydraulic conductivity) parameters for soil cover in the hillslope deposits in Tuscany (Italy) has been interpreted in order to improve the preparation of parameters for regional physically-based landslide prediction models.

An important finding, while examining the database, is that grouping the geotechnical parameters measurements with respect soil types (USCS classification) and bedrock lithology, substantially fails in giving back clearly distinguishable range of values for the different types of soils or bedrock. Indeed, in most cases the grain size distribution of soils is controlled by the intensities and the type of the acting slope processes regardless of from what bedrock typology they originated. For the same reason shear strength and hydraulic conductivity are difficult to predict on the basis of the geo-lithological maps only.

However, we have found that, instead, linkages between the different USCS soil types with morphometric parameters such as the profile of curvature of the hillslopes exist. This finding could be a starting point to develop alternative strategies to spatially organize and group in classes the geotechnical parameters.

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References

Alvioli M, Baum RL (2016) Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface. Environ Model Softw 81:122–135

Amoozegar A (1989) Compact constant head permeameter for measuring saturated hydraulic conductivity of the vadose zone. Soil Sci Soc Am J 53:1356–1361

Arnone E, Noto LV, Lepore C, Bras RL (2011) Physically—based and distributed approach to analyse rainfall-triggered land- slides at 320 watershed scale. Geomorphology 133(3):121–131

Baroni G, Facchi A, Gandolfi C, Ortuani B, Horeschi D, van Dam JC (2010) Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity. Hydrol Earth Syst Sci 14:251–270

Baum R, Savage WZ, Godt JW (2002) Trigrs: a FORTRAN program for transient rainfall infiltration and grid-based regional slope-stability 322 analysis. Open-file report, US Geol. Survey

Baum RL, Godt JW, Savage WZ (2010) Estimating the timing and location of shallow rainfall-induced landslides using a model for transient unsaturated infiltration. J. Geophys Res 115:F03013

Bicocchi G, D'Ambrosio M, Rossi G, Rosi A, Tacconi-Stefanelli C, Segoni S, Nocentini, M, Vannocci, P, Tofani V, Casagli N, Catani F (2016) Geotechnical in situ measures to improve landslides forecasting models: a case study in Tuscany (Central Italy). In: Proceedings ISL 2016 congress, pp 419–424. ISBN 9781138029880

Bicocchi G, Tofani V, D'Ambrosio M, Tacconi-Stefanelli C, Vannocci P, Casagli N, Lavorini G, Trevisani M, Catani F (2019) Geotechnical and hydrological characterization of hillslope deposits for regional landslide prediction modeling. Bull Eng Geol Env 78:4875–4891

Boccaletti M, Guazzone G (1974) Remnant arcs and marginal basins in the Cenozoic development of the Mediterranean. Nature 252:18–21. https://doi.org/10.1038/252018a0

Chen HX, Zhang LM (2014) A physically-based distributed cell model for predicting regional rainfall-induced shallow slope failures. Eng Geol 176:79–92. https://doi.org/10.1016/j.enggeo.2014.04.011

Fanelli G, Salciarini D, Tamagnini C (2016) Reliable soil property maps over large areas: a case study in central Italy. Environ Eng Geosci 22:37–52

Giannecchini R, Naldini D, D'Amato Avanzi G, Puccinelli A (2007) Modelling of the initiation of rainfall-induced debris flows in the Cardoso basin (Apuan Alps, Italy). Quat Int 171–172:108–117

Jia N, Mitani Y, Xie M, Djamaluddin I (2012) Shallow landslide hazard assessment using a three dimensional deterministic model in a mountainous area. Comput Geotech 45:1–10

Luttenegger JA, Hallberg BR (1981) Borehole shear test in geotechnical investigations. Am Soc Test Mater Spec Publ 740:566–578

Martini IP, Vai GB (2001) Anatomy of an Orogen: the Apennines and adjacent mediterranean basins. Kluwer, Dordrecht. 633 pp. https://doi.org/10.1007/978-94-015-9829-3

Masi EB, Bicocchi G, Catani F (2020) Soil organic matter relationships with geotechnical-hydrological parameters, mineralogy and vegetation cover of hillslope deposits in Tuscany (Italy). Bull Eng Geol Environ. Accepted

Mercogliano P, Segoni S, Rossi G, Sikorsky B, Tofani V, Schiano P, Catani F, Casagli N (2013) Brief communication: a prototype forecasting chain for rainfall induced shallow landslides. Nat Hazards Earth Syst Sci 13:771–777

Montrasio L, Valentino R, Losi GL (2011) Towards a real-time susceptibility assessment of rainfall-induced shallow landslides on a regional scale. Nat Hazards Earth Syst Sci 11:1927–1947

Pack R, Tarboton D, Goodwin C (2001) Assessing terrain stability in a GIS using SINMAP. In: 15th annual GIS conference, GIS

Park HJ, Lee JH, Woo I (2013) Assessment of rainfall-induced shallow landslide susceptibility using a GIS-based probabilistic approach. Eng Geol 161:1–15

Peres DJ, Cancelliere A (2014) Derivation and evaluation of landslide triggering thresholds by a Monte Carlo approach. Hydrol Earth Syst Sci 18:4913–4931. https://doi.org/10.5194/hess-18-4913-2014

Raia S, Alvioli M, Rossi M, Baum RL, Godt JW, Guzzetti F (2014) Improving predictive power of physically based rainfall-induced shallow landslide models: a probabilistic approach. Geosci Model Dev 7:495–514. https://doi.org/10.5194/gmd-7-495-2014

Ren D, Fu R, Leslie LM, Dickinson R, Xin X (2010) A storm-triggered landslide monitoring and prediction system: formulation and case study. Earth Interact 14:1–24

Ren D, Leslie L, Lynch M (2014) Trends in storm-triggered landslides over Southern California. J Appl Meteor Climatol 53:217–233

Rossi G, Catani F, Leoni L, Segoni S, Tofani V (2013) HIRESSS: a physically based slope stability simulator for HPC applications. Nat. Hazards Earth Syst Sci 13:151–166

Rosso R, Rulli MC, Vannucchi G (2006) A physically based model for the hydrologic control on shallow landsliding. Water Resour Res 42:W06410. https://doi.org/10.1029/2005WR004369

Salciarini D, Fanelli G, Tamagnini C (2017) A probabilistic model for rainfall-induced shallow landslide prediction at the regional scale. Landslides 14:1731–1746

Salvatici T, Tofani V, Rossi G, D'Ambrosio M, Tacconi Stefanelli C, Masi EB, Rosi A, Pazzi V, Vannocci P, Petrolo M, Catani F, Ratto S, Stevenin H, Casagli N (2018) Regional physically based landslide early warning modelling: soil parameterisation and validation of the results. Nat Hazards Earth Sys Sci 18:1919–1935. https://doi.org/10.5194/nhess-18-1919-2018

Segoni S, Leoni L, Benedetti AI, Catani F, Righini G, Falorni G, Gabellani S, Rudari R, Silvestro F, Rebora N (2009) Towards a definition of a real-time forecasting network for rainfall induced shallow landslides. Nat Hazards Earth Syst Sci 9:2119–2133

Simoni S, Zanotti F, Bertoldi G, Rigon R (2008) Modelling the probability of occurrence of shallow landslides and channelized debris flows using geotop-fs. Hydrol Process 22:532–545

Tao J, Barros AP (2014) Coupled prediction of flood response and debris flow initiation during warm- and cold-season events in the southern Appalachians USA. Hydrol Earth Syst Sci 18:367–388

Tofani V, Bicocchi G, Rossi G, Segoni S, D'Ambrosio M, Casagli N, Catani F (2017) Soil characterization for shallow landslides modeling: a case study in the Northern Apennines (Central Italy). Landslides 14:755–770. https://doi.org/10.1007/s10346-017-0809-8

Wagner AA (1957) The use of the unified soil classification system by the Bureau of Reclamation. In: Proceedings of the 4th international conference on soil mechanics and foundation engineering, London vol I, 125 pp

Zizioli D, Meisina C, Valentino R, Montrasio L (2013) Comparison between different approaches to modeling shallow landslide susceptibility: a case history in Oltrepo Pavese. Northern Italy. Nat Hazards Earth Syst Sci 13:559–573