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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "From slope- to regional-scale shallow landslides susceptibility assessment using TRIGRS" *by* M. Bordoni et al.

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The authors are grateful to the Anonymous Referee #1, whose comments and suggestions will contribute towards an improvement of the final paper. Point-by-point replies to the referee's comments follow.

Reply to introductory comments by the reviewer

As reported in the Introduction, the paper deals with a definition of a methodology for the application of physically based-models for shallow landslides at different scales, extending the slope stability analysis from the slope scale (area in the order of less than 1 square kilometer) to basin or regional scale (area of several or tens square kilometers). In the following, we explain which are the main innovative aspects. 1) The

proposed working scheme for the implementation of the well-established physically-based model TRIGRS-Unsaturated aims at finding a potential loop between different scales of analysis. In particular, it is intended to answer the following question: in which way modeling the soil hydrological behaviors leading to shallow landslides triggering can be extended from a slope-scale observation to the regional scale. We retain that an improvement on the results of the model application can be obtained through the use of hydrological monitoring data in correspondence of a slope, which can be considered representative of the geomorphological, geological and physical condition of the surrounding area. In particular, the monitoring approach allows to identify the typical soil behaviors along different seasons, allowing for better understanding the response of the slopes to different rainfalls. 2) The approach followed in this work also allows for verifying the reliability of modeled hydrological parameters (such as pore water pressure) trends during different rainfall conditions. The assumption according to which the modeled hydrological parameter trends on wide areas should correspond to the real physical processes without an experimental confirmation, can cause errors on the assessment of shallow landslides initiation. For this reason we propose a verification of the reliability of the model results, even if it necessarily involves only few sample points. 3) This work gives some indications about the influence of the type of mapping unit chosen for the homogenization of the soil parameters, which are required as input data for the model application at regional scale. In most cases the mapping units used in distributed slope stability analyses are defined according to the geology of the bedrock (Salciarini et al., 2006; Baum et al., 2010; Sorbino et al., 2010; Rossi et al., 2013; Park et al., 2013; Zizioli et al., 2013). This choice is linked to the hypothesis that the geotechnical and hydrological properties have spatial variations due to the spatial distribution of the bedrock materials whence soils derive. Instead, it is important identifying, if there are, some differences on model results considering other types of mapping units, as the unit linked to the pedological classification of the soil deposits. The choice of the pedological unit is linked to the distinction of the soils of a study area on the basis of their pedological features, which can be connected to different pedological processes that can influence directly the physical and hydrological behavior of a soil (Baumhardt and Lascano, 1993). The analysis of the role played by mapping unit described in this paper aims to identify which mapping unit is more representative of the distribution of the soil properties all over the study area. This aspect is usually neglected on the application of distributed physically based models, but it can lead to improve the results of the landslides susceptibility assessment. The authors retain that the comments and the suggestions of the reviewer can give an improvement to the paper, also in terms of explaining the innovations of the research.

Reply to Comment 1

The use of terms such as “susceptibility analysis” and “susceptibility map” are used in the paper with reference to what expressed by Corominas et al. (2014). In literature, many works used the rainfall conditions of a real event as input data for the implementation of a physically based model which returned a landslides susceptibility assessment (Salciarini et al., 2006; Liao et al., 2011; Sorbino et al., 2010; Park et al., 2013; Zizioli et al., 2013). Moreover, considering a real rainfall event allows for identifying the unstable slopes of a study area in relation to particular rainfall conditions and, then, the areas where slope failures can develop. In this sense, the analysis carried out in the paper can represent a landslides susceptibility analysis. On the other hand, we are aware that a more appropriate susceptibility analysis for the study area would require the assessment of several rainfall scenarios, and that the performances of the model would be related to the uncertainties of field data, soil properties and rainfall, but it was beyond the scope of this paper. Then, by acknowledging the reviewer’s suggestion, we will modify the text by using a different terminology. For the same reason, we will modify the title of the paper as follows: “From slope- to regional-scale analysis of shallow landslides triggering zones using TRIGRS”. The paper provides a validation and a quantitative assessment of the performance of the TRIGRS-Unsaturated model against real recent landslides, in terms of success and error indexes taken from literature, by considering the following aspects: 1) a reliability verification of the model

results in terms of hydrological parameters, on the basis of field measurements; 2) a sensitivity analysis of the model with respect to the type of mapping unit chosen to select the soil properties all over the study area. In the paper, a validation procedure more than a real calibration of the soil input data has been performed, because the authors intended to assess the distributed slope instability by using as input data the real available soil geotechnical, physical parameters and hydrological properties obtained through pedotransfer function (Rosetta model) over the study area. Instead, in the reply to reviewer’s comment 3, we will explain the effects on the model performance linked to the uncertainties of the soil input parameters. As regards the transfer from local to regional scale, it is worth noting that beside the depth of the perched water table, an important phase of the methodology is represented by the hydrological parameters of soils in unsaturated conditions. In fact, it is well known that an appropriate modeling at local scale needs SWCC based on both field and experimental tests. It is not possible to take for granted that assuming at regional scale the same hydrological parameters as at local scale should attain good results. On the other hand, the use of pedotransfer functions without an experimental confirmation, can lead to unreliable results. For the considered case study, we propose a verification of the hydrological parameters from pedotransfer functions, although it is based only on few experimental results. Among experimental data, those acquired at the monitoring station at different depths were particularly useful to infer the average parameters assumed for a homogeneous soil at regional scale.

Reply to Comment 2

Following the comments and the suggestions of the Referee #1, the authors describe more in detail the hydrological features at regional scale in the study area. The study area is constituted by a medium low-permeability arenaceaous conglomeratic bedrock (Monte Arzolo Sandstones and Conglomerates of Rocca Ticozzi) overlying impermeable silty-sandy marly bedrock (Sant’Agata Fossili Marls). The strata are sub-horizontal, dipping east-northeast. The medium low- hydraulic conductivity of the arenaceous-conglomeratic bedrock is linked to its low primary porosity and to the limited number of fractures which cannot cause the development of a high secondary hydraulic conductivity. The deep water circulation is then confined in less cemented or more fractured levels, located at different depths in the bedrock. In the area surrounding the monitored slope, these levels correspond to horizons of poorly cemented gravels, sands or conglomerates, with a limited lateral extension and thickness ranging between 0.2 and 1.0 m. These bodies do not seem constituting a continuous more permeable level which can form a deep aquifer. The presence of water in the bedrock can be identified only in correspondence of the more permeable levels as isolated bodies. A limited number of springs are detected only in the valley bottom in correspondence of the contact between the arenaceaous conglomeratic bedrock and the sandy-silty marls. These springs are detected only during the more rainy period of winter and spring months. The difference in elevation between the top of the monitored slope and the valley floor is of 132 m, while the difference in elevation between the position of the monitoring station and the Rio Frate Creek is of 63 m. Another evidence demonstrates the absence of a deep groundwater level. Fig. 1 shows the trends of water electrical conductivity measured through the TDR probes of the monitoring station at different depths in soil and weathered bedrock levels . The electrical conductivity values range between 15 and 40 μS/cm in the soil profile till 1.0 m from ground level, with the highest values in correspondence of wet periods characterized by more frequent rainfalls. In the same periods, at 1.2 m from ground level, the water electrical conductivity reaches values till 50 μS/cm. Weathered bedrock level at 1.4 m from ground has values in a similar range with respect to the more shallow soil horizons (Fig. 1). According to these data, it seems clear that there is no uprising of a deep water table from the bedrock to the superficial soil, as testified by the values of water electrical conductivity in the range of the rainfall water. Moreover, the highest values measured at 1.2 m from ground in the G horizon during the winter and spring months testify the temporary formation of a perched water table in correspondence of this profile, which can rise in correspondence of more intense rainfall events up to the more shallow levels (Fig. 1). On the basis of

these observations, the development of a thin perched water table above the contact soil-bedrock seems to be the most believable hydrological mechanism, even if others mechanisms (e.g bedrock exfiltration; Brönnimann et al., 2013) cannot be completely excluded.

Reply to Comment 3

Considering the soil samples used for obtaining the soil properties, we indicate that 114 disturbed soil samples were used to measure Atterberg limits and grain size distribution curves, while 52 undisturbed soil samples were used to measure soil unit weight. In the group of undisturbed soil samples, taken at a depth where the failure surface of shallow landslides developed, 18 samples were used to measure peak shear strength parameters through direct shear tests and 3 samples for triaxial tests. We propose to add in Tab. 5 of the original paper the standard deviation of each parameter required by the model, also modifying the title of the table in "Table 5. Mean and standard deviation (sd) values of the soil parameters used as input data in TRIGRS-Unsaturated. The standard deviation values are in parentheses.". In this way, it will be possible to consider the potential variation of each soil parameter of a particular mapping unit. The modified table is on the supplement attached to this reply. To take into account the uncertainties of the soil input data, we will add in the paper the results of a sensitivity analysis. The sensitivity analysis has been carried out by changing only one parameter in each simulation, keeping steady the other ones. We considered as variables the unit weight γ, the peak friction angle φ', the effective cohesion c' and the hydrological parameters (θs, θr, αG, Ks, D0). We made different simulations by considering for each parameter either the mean value or the value obtained by subtracting or adding its standard deviation. For c' parameter, we set its minimum value equal to 0 kPa. The results of the sensitivity analysis is shown in Fig. 2. As suggested by the reviewer, the correct terminology of True Positive Rate (TP) in place of Success Index (SI) and False Positive Rate (FP) in place of Error Index (EI) has been used. We will correct the terminology in the text of the paper and in the figures of the paper where the terms are present. A negligible variation of both the True Positive Rate (TP) and the False Positive Rate (FP) are linked to the analysis of the influence played by γ parameter (Fig. 2a), with values changing in the order of 0.9 and 2.3% for geological and pedological unit mapping, respectively. As regards the hydrological parameters, the best results in terms of TP are obtained by considering the mean values, with an improvement in the order of 12.3-21.2% with respect to the values including the standard deviation. Instead, FP values keep substantially steady in all the simulations (Fig. 2d). Greater variations affect both TP and FP indexes by changing φ' and c' (Fig. 2b, c). The lowest values of these parameters determine an improvement on the correct identification of the real unstable areas, as indicated by the increase in TP up to 7.3%, but at the same time they lead to an increase of the areas wrongly mapped as unstable, as indicated by an increase in FP values up to 37.1%. In this case, a nil value of cohesion for both pedological mapping units (Fig. 2b, c) has been assumed. The highest values of φ' and c' cause a slight decrease in FP, ranging between 0.2 and 5.7%, and a significant decrease in TP, ranging between 40.4 and 44.3% (Fig. 2b, c). A further index useful to evaluate the model performance is represented by the ratio between TP and FP. For each unit mapping, the highest ratio between TP and FP corresponds to the simulation obtained by considering the mean values of the soil input data for all the units. In particular, for the pedological unit mapping it is slightly higher than for the geological one. The mean values of the soil input data seem to be representative of the units that characterize the study area, and they seem to attain the best results in all the sensitivity analyses. As regards the simulation of some representative rainfall events for TRIGRS validation, a possible solution to improve the fitting of pore water pressure could be considering a double-layer soil with different hydrological properties, instead of assuming mean values for the entire soil profile, as required by TRIGRS. In fact, as demonstrated by the values reported in Table 2, the layers at 0.6 and 1.2m from ground level are characterized by different hydrological parameters. To get a best fitting of the experimental data, it could be possible to model separately the pore water pressure at 0.6m, by assuming a unique soil layer 0.6m thick, and at 1.2m, by assuming a unique

soil layer 1.2m thick, but this procedure would not be consistent with the distributed analysis, since TRIGRS does not allow to consider a layered soil. For these reasons we considered appropriate to simulate the pore water pressure by assuming only mean values of hydrologic parameters of different layers from laboratory tests. Indeed, the mismatch is always lower than 2kPa, and only in correspondence of the rainfall event of 28 February 2014 the mismatch attains a value of 2.8kPa. It is true that, in general, the variation could have the same range of the mismatch, and then the error could be more than 100% of the variation, but we must consider at least the following aspects: a) The goodness of these results should be evaluated not in an absolute sense, with respect to only isolated rainfall events, but in relation to long-period analyses; b) During the considered rainfall events, modeled value of pore water pressure is always higher than the measured one; in its turn, overestimated pore pressure cause an underestimation of the Safety Factor of the slope, thus ensuring precautionary conditions; c) Although the results could be considered not satisfactory at the local scale, the intrinsic limitations of the TRIGRS model (such as the use of a homogeneous soil) together with the extreme potential variation of hydrologic parameters at regional scale would make not consistent a sensitivity analysis at local scale.

Reply to Comment 4

As already indicated in the Reply to Comment 3, we thank the Reviewer for the correction about the terminology. In the revised version of the paper we will substitute, the terms of Success Index (SI) and Error Index (EI) with True Positive Rate (TP) and False Positive Rate (FP), respectively. We also thank the Reviewer for the individuation of the error on the definition of True Positive Rate (TP). We will substitute the text at Page 17 - Lines 2-4 with the following text: "the ratio (in percentage) between the number of elementary cells computed as unstable (safety factor < 1.0) by the model and the number of elementary DEM (Digital Elevation Model) cells occupied by shallow landslides.".

Reply to Comment 5

As suggested by the reviewer, we will submit the paper to a proof English review to improve the written presentation of the work and to make the paper more fluent and understandable.

We will add the following reference to the original paper:

Brönnimann, C., Stahli, M., Schneider, P., Seward, L., and Springman S. M.: Bedrock exfiltration as a triggering mechanism for shallow landslides, Water Resour. Res., 49, 5155–5167, doi:10.1002/wrcr.20386, 2013.

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervas, J., and Smith, J. T.: Recommendations for the quantitative analysis of landslide risk, Bull. Eng. Geol. Environ., 73, 209-263, 2014.

Please also note the supplement to this comment:
http://www.nat-hazards-earth-syst-sci-discuss.net/2/C3211/2015/nhessd-2-C3211-2015-supplement.pdf

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 7409, 2014.

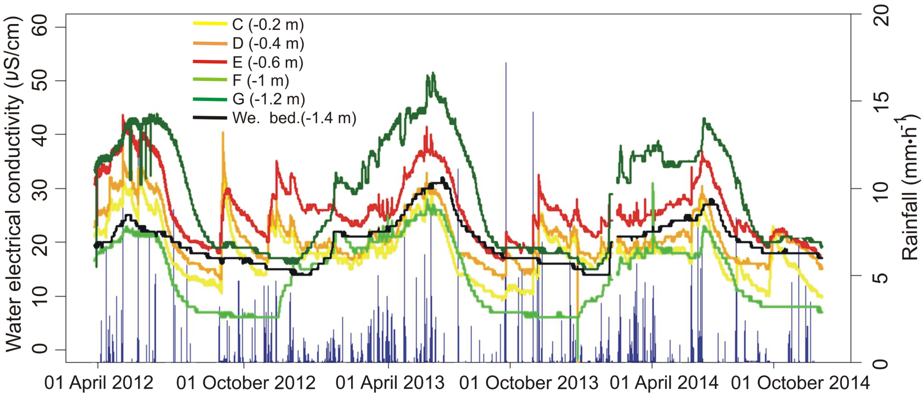

Fig. 1. Monitored soil and weathered bedrock water electrical conductivity dynamics at the monitored test-site slope in the study area.

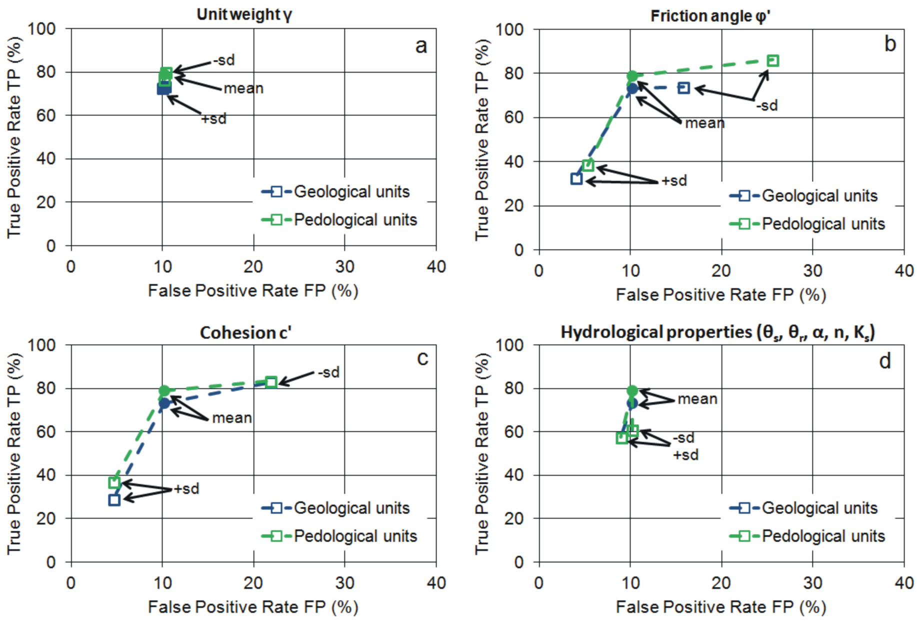

Fig. 2. Effects of different soil input data on FP and TP indexes obtained modeling with TRIGRS-Unsaturated considering the values in Table 5.