Lecture Notes in Civil Engineering

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Geotechnical Research for Land Protection and Development

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Editors

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Preface

The Italian Conference of Researchers in Geotechnical Engineering—CNRIG—reached this year its seventh edition, three years after the successful conference held in Bologna in 2016. The conference was promoted by the National Group of Geotechnical Engineering (GNIG; http://www.gnig.it/) and hosted by Politecnico di Milano (https://www.polimi.it/) at the campus in Lecco (Polo Territoriale di Lecco, http://www.polo-lecco.polimi.it/en). The conference provides an important opportunity to share scientific advances, innovation, and application in geotechnical engineering and is becoming a traditional event for the Italian geotechnical community.

The focus chosen for the conference "*Geotechnical Research for Land Protection and Development*" faces two of the most relevant issues in civil and environmental engineering, which have a key role in modern societies and in our country in particular. The evaluation of the environmental and economic impact of strategies for the protection and the development of the built environment requires a multidisciplinary approach encompassing thorough analyses of their sustainability in the long term. Geotechnical engineering is a core discipline in this process, as it brings advanced knowledge of the physical processes occurring in the subsoil, hence, informed evaluation of the environment vulnerability and of the potential of innovative technical solutions.

As a tradition of this series of conferences, which foster lively debate on recent research advancements, the event provides the participants with a great opportunity to share up-to-date knowledge, experiences and new ideas, as well as to discuss current research projects and potential future collaborations. In this perspective, the choice of English as the official language of the conference proceedings gave the authors the opportunity to share their works beyond the national level and to reach worldwide diffusion thanks to the highly reputed series of Lecture Notes in Civil Engineering, edited by Springer.

The papers submitted for publication were peer-reviewed by the Scientific Committee and by selected members of the GNIG. The eighty-two papers accepted for publication show recent scientific advances on the topic of the conference, as well as promising ongoing research initiatives in Italy, or involving Italian

researchers. We proudly observe that more than 250 colleagues co-authored the papers, with a significant part (almost 10%) of non-Italian researchers, witnessing the good international networking of the Italian geotechnical community.

These proceedings contain two sections, following the organization of the conference. *Section 1 Protection* discusses the role of geotechnical research in the mitigation of risks for the built environment, including structures, infrastructure, strategic lifelines, deriving from earthquakes, floods, landslides or contaminant diffusion, either at ultimate or serviceability limit conditions. *Section 2 Development* is devoted to the geotechnical contribution to the construction of new structures or infrastructure, in the use of underground space, on sustainable solutions when dealing with problematic soils, with particular emphasis on their design approaches and on their interaction with the environment.

We are sincerely grateful to all the authors for their contribution to this volume and to the Scientific Committee and the members of GNIG for the high effort in reviewing all the contributions. We think this definitely represents a good example of the vitality of the Italian community of researchers in geotechnical engineering. A warm thank to the members of the organizing committee for their passionate and tireless help in providing effective (and, very often, real time!) solutions to all the countless needs of the organization of such a prestigious event as CNRIG 2019.

We hope the content of this volume to be of valuable and long-time lasting interest to researchers in geotechnical engineering.

July 2019

Francesco Calvetti
Federica Cotecchia
Andrea Galli
Cristina Jommi

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Protection

Influence of Numerosity and Distribution of Piezometric Data on the Performance of a Warning Model for Weather-Induced Landslides in Norway

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Abstract. Territorial landslide early warning systems (Te-LEWS) are widely applied worldwide to deal with weather-induced landslides over wide areas, typically through the prediction and forecasting of meteorological parameters. However, meteorological monitoring alone does not allow to take into account critical soil conditions controlling the triggering process. Depending on local conditions, landslides may be triggered in response to a large variety of weather events. Therefore, the integration of geotechnical monitoring data within warning models for weather-induced landslides at regional scale can provide supplemental information useful to determine the likelihood of a given weather event actually producing landslides.

A methodology designed to integrate widespread meteorological monitoring and pore water pressure measurements is herein applied within 30 hydrological basins highly susceptible to weather-induced landslides in Norway. The correctness of the predictions in relation to different network configurations of the piezometers is evaluated through a series of parametric analyses. The results of a first application of the proposed warning model are also presented and discussed. This study should be considered as a first attempt to define the conditions for adopting an economically sustainable and technically reliable geotechnical monitoring strategy for predicting the conditions leading to the triggering of weather-induced landslides over wide areas.

Keywords: LEWS · Warning model · Monitoring · Pore water pressure · Parametric analysis

1 Introduction

Recent literature contributions described many landslide early warning systems deployed to address weather-induced landslides both at regional and slope scale all around the world (Pecoraro et al. 2019b; Piciullo et al. 2018). At regional scale, the warning models are mainly based on the prediction and monitoring of hydrometeorological variables in order to assess the probability of landslide occurrence (Segoni et al. 2018). However, the mechanisms that lead to slope instability are typically influenced by a series of local factors (e.g., soil properties), thus a direct relation

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between rainfall and landslide initiation cannot be always determined (Staley et al. 2012). Baum and Godt (2010) stated that geotechnical monitoring could provide useful indication in areas where soil moisture exhibits strong seasonal variation. Stähli et al. (2015) proposed to combine local measurements of landslide precursors with model predictions at catchment scale. Recently, Calvello (2017) pointed out that local observations may provide fruitful indications on the local conditions of the study area.

This study aims at integrating local pore water pressure measurements collected at local scale and widespread meteorological monitoring. The proposed methodology is applied to 30 hydrological basins in Norway, highly susceptible to weather-induced landslides. Firstly, three parametric analyses are conducted in order to determine the most appropriate time period for the trend analyses and to assess the influence of the network configurations of the piezometers on the results. Then, the warning events issued applying the warning model employed within the national LEWS operational in Norway (Piciullo et al. 2017) are further scrutinized considering the local observations.

2 Study Areas and Available Datasets

The Norwegian hydrological basins have been considered appropriate territorial units for which pore water pressure observations may provide meaningful information for analyses at catchment scale. The national catchment database REGINE shows that the Norwegian water system is divided into 22,545 basins, defined as polygons covering the whole country. The subdivisions of the water system areas form a hierarchy, thus the drainage area of each territorial unit may vary by orders of magnitude, ranging from less than 10^{-4} km^2 for basins draining a well-defined small torrent to more than 10^4 km^2 for large river basins. Among them, 30 hydrological basins have been identified as potentially useful for the analyses according to two main criteria: the occurrence of shallow landslides in loose soils and the availability of a relevant number of locations with pore water pressure measurements. The majority of them (16 out of 30) are distributed along the western coast of Norway; the remaining 14 basins are situated in the south-eastern part of the country.

The data on landslide occurrences were retrieved from the national landslide database (www.skrednett.no), which contains more than 60,000 entries (represented by point locations) covering the whole country. A total of 125 weather-induced landslides in soils occurred in the test areas in the period of analysis, i.e., from January 2013 to June 2017. 58 of these records are characterized as landslides in soil (46.40%), not otherwise specified due to lack of further documentation; 45 (36.00%) are classified as debris flows, debris avalanches or mudslides; 13 (10.40%) are reported as soil slides in artificial slopes (cuts and fillings along road and railway lines); 5 (4.00%) are slush flows and the remaining 4 (3.20%) are clay slides. In the majority of the basins (25 out of 30), the number of landslides varies between 3 and 5, yet four basins were interested by 6 landslides and the remaining one by 7 landslides.

The pore water pressure measurements were collected at local scale analysing data from 41,706 boreholes installed by NGI for a variety of geotechnical projects throughout Norway not specifically aimed at early warning purposes, such as: geotechnical site characterization of soils; slope stability analysis; efficiency evaluation

of surface drainage works; monitoring of road and railway embankments. The piezometers considered representative of conditions which led to the triggering of the landslides have been selected taking into account their spatial proximity to the landslides that occurred in the period of analysis, and the installation in the shallower soil layers or in areas characterized by the presence of loose sediments. It is worth mentioning that data from only electric piezometers have been considered, as they provide longer and more reliable data series. Pore water pressure measurements recorded in the period of analysis within the test areas were derived from 240 boreholes, whose numerosity varies between 7 and 14.

3 Methodology

In a preliminary phase, pore water pressure trends have been derived from the piezometric data available within each territorial unit in the period of analysis. As the records are typically characterized by a significant short-term variability, they have been statistically processed in order to smooth the short-term fluctuations and to make the identification of potential trends possible. To this aim, the simple moving average of the recorded pore water pressures at a given day (u_i) has been calculated, over the number of days of a specified time period (n), as follows:

$$u_i = \sum_{k=i-n+1}^{i} \frac{p_k}{n}. \tag{1}$$

where p_k is the pore water pressure recorded at day k. Then, two indicators of pore water pressure variations have been defined, as follows:

$$\Delta u_i = u_i - u_{i-n}. \tag{2}$$

$$\Delta u_i^* = \frac{u_i}{u_{imax}}. \tag{3}$$

where Δu_i is the difference between the simple moving averages calculated considering a length equal to n days and referring to days i and $i - n$; and Δu_i^* is the same difference normalized by the maximum difference observed in the dataset, Δu_{imax}.

Successively, three parametric analyses have been conducted in order to assess the correlations between the day of occurrence of the landslides and the pore water pressure trends in relation to different operative conditions within each territorial unit (Fig. 1a, b). The first parametric analysis has been carried out in order to identify the most appropriate time period (n) for calculating the simple moving average differences, Δu_i. Moreover, the influence of the network configurations of the piezometers (i.e., numerosity of the piezometers and average distance from the landslides) on the reliability of the predictions has been evaluated.

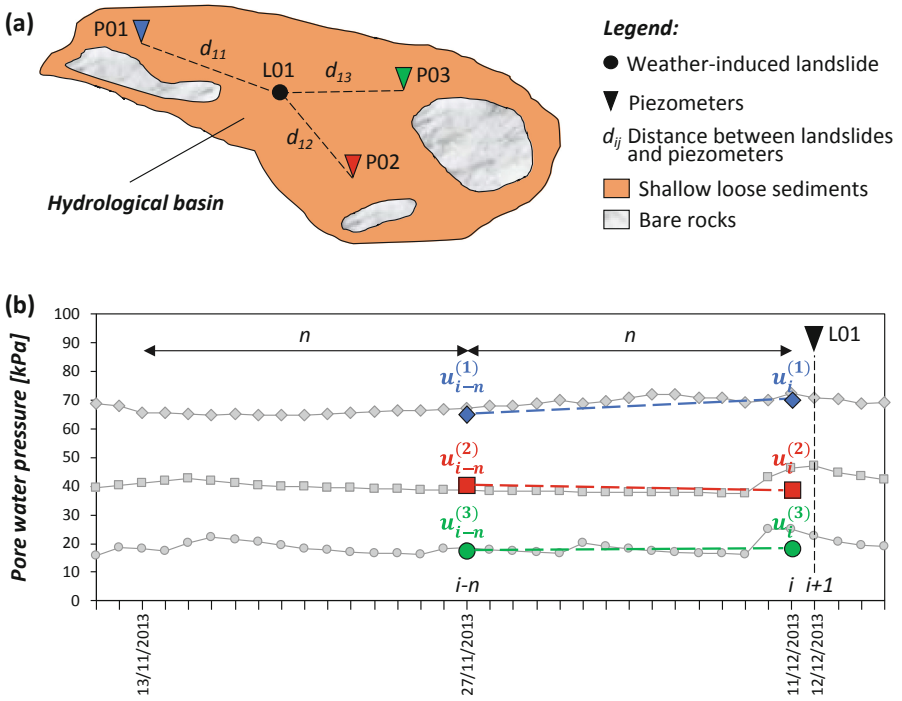

Fig. 1. Example of application of the proposed methodology to the test areas: identification of weather-induced landslides and available piezometers (a) and pore water pressure trend analyses (b)

Finally, the pore water pressure observations collected at local scale have been used to assess the warning events issued by applying the regional model to one of the selected territorial units, following the 2-step procedure proposed by Pecoraro et al. (2019). In the first step, the differences between the simple moving averages referring to days i and $i - n$ are evaluated. In case they do not show a clear trend, the warning level issued by the regional model (WL_0) is maintained. Otherwise, a second step is performed wherein the normalized simple moving average differences are compared with pre-defined thresholds. Three final outcomes are possible: the confirmation of the same warning level issued by the regional warning model, an increase of the warning level, a decrease of the warning level. No more than two warning level variations are allowed.

4 Parametric Analyses

4.1 Time Periods

In the first parametric analysis, the possible trends of Δu_i have been evaluated over time periods (n) of 1, 2, 3, 4, 5, 6, 7, and 14 days. Short time periods have been considered because pore water pressure variations possibly triggering a landslide in shallow loose sediments are typically recorded few days before a landslide event. Besides, a short-term moving average allows identifying possible significant trends without any significant temporal lag between the original and the average data series caused by longer window lengths. The moving average trends have been evaluated considering the 125 weather-induced landslides that occurred in the period of analysis. It is worth highlighting that in these cases an uptrend, i.e. an increase of pore water pressure moving averages, can be considered as a correct indicator, whereas a downtrend has to be considered an incorrect indicator. "No trend" indicates that the moving average differences do not show a clear trend. Figure 2 highlights an overall good correlation between the landslides and the pore water pressure observations, as more than 50% of the events are associated to uptrends for all the considered time periods. The percent difference between correct and incorrect indicators increases with the length of the time period. Indeed, Δu_{14} shows the highest value of this difference (61%), as 77% are correct indicators (96 out of 125), 16% are incorrect indicators (20), and the remaining 7% (9) do not show any trend. Therefore, Δu_{14} can be considered the most appropriate indicator to adopt for the successive analyses.

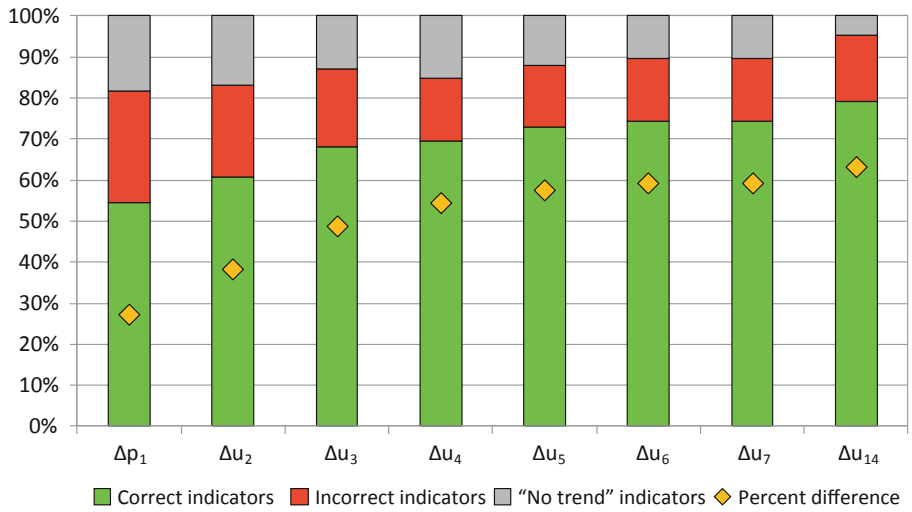

Fig. 2. Influence on the correctness of the results of the time period used for the calculation of the simple moving average differences (Δu_i)

4.2 Numerosity

The second parametric analysis has been conducted in order to assess the influence of the numerosity of the piezometric locations on the correctness of the results. The number of piezometers available for each landslide that occurred in the period of analysis varies between 2 and 7. They have been grouped in four numerosity classes (2, 3, 4 and 5 or more piezometers) so that a reasonable number of data is available in each class for supporting the analyses. The moving average trends have been evaluated in order to identify the uptrends (correct indicators) associated to the landslides for each class, following the same procedure adopted for the first parametric analysis. Figure 3 highlights that the majority of the landslides are associated to uptrends, regardless to the numerosity of piezometric data. Yet, the correctness of the predictions increases passing from 2 (66%) to 5 or more piezometers (88%). Moreover, the upper class is characterized by the highest percent difference between correct and incorrect indicators (82%), as only in 2 cases out of 17 there is not coherence between landslides and piezometric data. This seems to suggest a positive correlation between the reliability of the predictions and the numerosity of piezometric data.

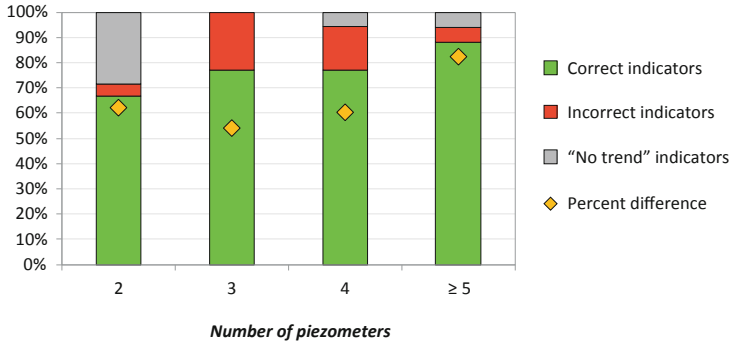

Fig. 3. Influence on the correctness of the results of the numerosity of piezometers

4.3 Average Distance

The third parametric analysis has been carried out in order to assess whether and how the reliability of the results depends on the average distance between the networks of piezometers and the landslides. Indeed, the significance of piezometric data collected at a certain distance from the landslide is a crucial issue to investigate before using them for early warning purposes. To this aim, the networks of piezometers have been grouped in four rather homogenous classes depending on their average distance from the landslides. Following the same criterion already adopted for the two other parametric analyses, the moving average trends have been evaluated in order to assess the number of correct indicators (i.e., uptrends) for each class (Fig. 4). As expected, the networks of piezometers installed in the proximity of the landslides (i.e., at a distance shorter than 500 m) provide the best results (83%) and only in 3 cases the occurrence

of a landslide is not characterized by an uptrend. However, the percent differences between correct and incorrect indicators observed for the four defined classes do not show significant variations, especially for average distances longer than 500 m. These results seem to suggest that the piezometric data available in each territorial unit can provide meaningful information for early warning purposes at this scale of analysis, regardless of their distance from the landslides.

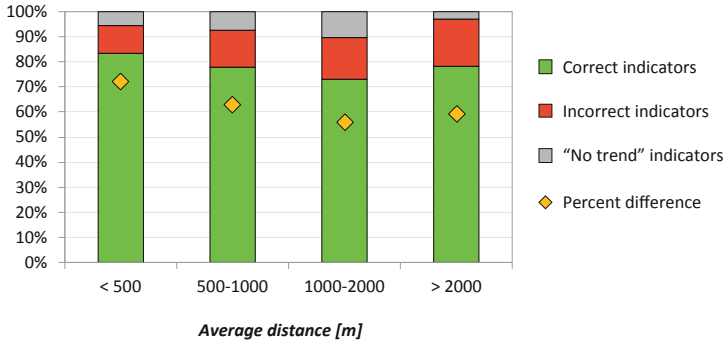

Fig. 4. Influence on the correctness of the results of the average distance between landslides and networks of piezometers

5 Application to One Territorial Unit

The warning model proposed by Pecoraro et al. (2019a) and aimed at integrating the regional gridded data employed by the national LEWS operational in Norway and the pore water pressure trends defined herein has been applied to the Glommavassdraget basin (Fig. 5a). The study area is situated in the south-eastern part of Norway and covers an area of about 27 km^2. The soil profile consists of loose sediments prone to landslides (59%), bare rocks (40%), and materials not prone to landslides (1%). From January 2013 to June 2017 (i.e. the period of analysis) the study area experienced 7 landslides; 5 of them can be classified as weather-induced landslides in soils. A total of 8 piezometers installed in the study area provided pore water pressure data for the analyses.

Firstly, the average values of the hydrometeorological variables calculated over the 42 grid-cells covering the basin have been compared with the four warning levels adopted by the national LEWS (Krøgli et al. 2018). This allowed identifying the days with warnings as well as defining, in these cases, the level of the warning (Fig. 5b). Table 1a displays that all the 5 landslides that occurred in the period of analysis were detected by the regional model: in 4 cases the model was in level 2 and in one case in level 4. On the other hand, 57 warnings have been issued when landslides did not occur: the majority being level 2 "moderate warnings" (44 events), and the rest of them being level 3 "severe warnings" (13 events).

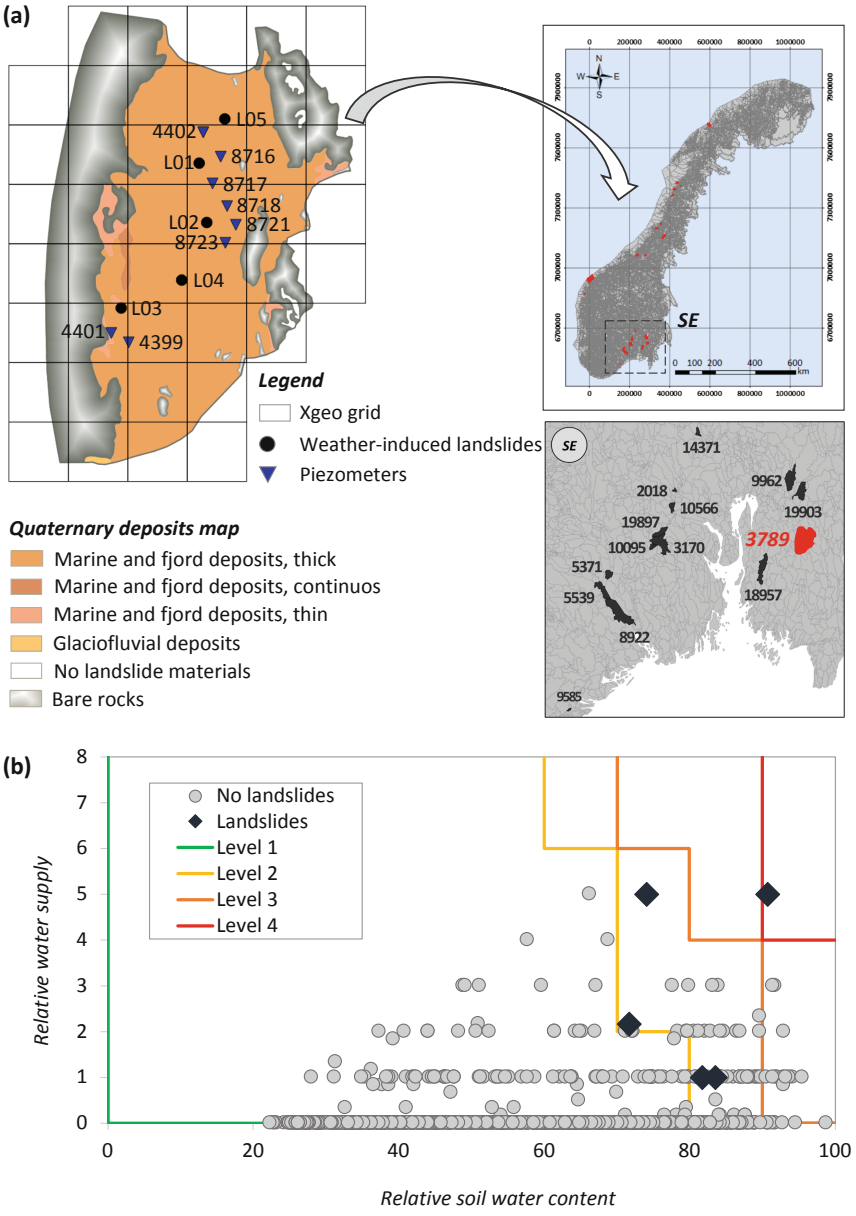

Fig. 5. Quaternary deposit map, landslides and piezometers in the test area, i.e. Glommavassdraget basin (a) and results obtained applying the regional warning model employed in the national LEWS (b)

Successively, the 62 warning events issued applying the regional model have been further scrutinized considering the local observations available in the study area, following the methodology described in Sect. 3. Table 1b reports that two landslide events originally classified as level 2 "moderate warnings" *(WL_2)* have been raised to level 3 "severe warnings" *(WL_3)* and another one to level 4 "very severe warnings" *(WL_4)*. The other two landslide events have been confirmed at level 2 and level 4, respectively. Moreover, looking at the warning events issued when landslides did not occur, two of the 13 "severe warnings" false alerts have been decreased to "moderate warnings", while 22 of the 44 "moderate warnings" false alerts have been no longer classified as alerts.

Table 1. Comparison between warning models employing widespread meteorological monitoring alone (a) and integrating local observations (b)

a)	WL_1	WL_2	WL_3	WL_4
Landslides	0	4	0	1
No landslides	1580	44	13	0

b)	WL_1	WL_2	WL_3	WL_4
Landslides	0	1	2	2
No landslides	1604	22	11	0

6 Conclusions

In the present study, the additional contribution of local pore water pressure measurements for early warning purposes in Norway was analyzed and discussed. Firstly, pore water pressure trends were calculated and their correlation with the landslides that occurred in the period of analysis was studied by means of three parametric analyses considering different time periods and network configurations of the piezometers. The first analysis highlighted that the best results were achieved considering the longest time periods $(n = 14\ days)$. The second analysis showed that the numerosity of the piezometric data available in each territorial unit partly affects the reliability of the results. On the other hand, the distance does not influence significatively the correctness of the predictions. This seems to suggest that at a catchment scale landslides are triggered by triggering conditions (i.e. rise of pore water pressure) widespread within the territorial unit.

An application of the warning model integrating widespread monitoring data and pore water pressure measurements collected at local scale was also carried out considering one of the territorial units. The preliminary results achieved herein highlight a huge potential for the local geotechnical observations to complement widespread meteorological monitoring. Indeed, local observations can provide meaningful information for territorial early warning systems addressing weather-induced landslides although, of course, the parameters to be included within the model need to be properly selected depending on the types of landslides under surveillance.

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Temporal Evolution of the Force Exerted by Dry Granular Masses Impacting on Rigid Sheltering Structures

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Abstract. In this paper, the Discrete Element approach is employed to study the evolution with time of the impact force exerted by dry granular flows on rigid obstacles and to better understand the impact mechanism. The dry granular mass is initially positioned in front of the wall with an assigned uniform velocity and porosity and the evolution with time of the impact force is evaluated. In particular, the influence of both mass initial porosity and front inclination on the impact force evolution has been investigated.

From a design point of view, the results integrate the formula that was previously introduced by the authors for the maximum impact force, by adding information about its time evolution.

Keywords: Impact · DEM · Porosity · Impulse · Granular materials

1 Introduction

The evaluation of the impact force exerted by granular flows on rigid obstacles is of fundamental importance for the design of sheltering structures.

In most of the practical approaches and standard, a pseudo-static approach is employed: the maximum impact force is estimated by using empirical formulas and it is applied to the barrier as a quasi-static force. A number of formulas are available in the literature for the maximum impact force evaluation; most of them are based on over-simplifying hypotheses about the behavior of the granular material and require the use of empirical correcting factors which vary in a wide range, making the practical use of these approaches rather arbitrary (Arattano and Franzi 2003; Armanini 1997; Bugnion et al. 2012; Hubl et al. 2009; Scotton and Deganutti 1997).

Considering the dynamic nature of impacts, the maximum impact force is not sufficient to design protection works and the impulse value should be used in design.

For this reason, the study of the time evolution of the impact force is of fundamental importance.

In this study, the Discrete Element Method (DEM) (Cundall and Strack 1979) has been employed to investigate the role of both initial porosity and front inclination on

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the impact force evolution. In fact, porosity represents a major parameter determining the type of granular flow. When the initial porosity is sufficiently low, the material behaves like a dense granular flow and force chains can develop within the mass. On the contrary for very large values of initial porosity, the material behaves like a granular gas and particles interacts through inelastic collisions (Jaeger et al. 1996; Redaelli et al. 2016). This different nature of the material, changes completely the impact phenomenon and the impact force evolution.

By employing the DEM, since the macroscopic behavior of the assembly derives directly from micromechanical parameters and state parameters, it is possible to take into account the local variation of porosity and internal microstructure deriving from compaction of the material during the impact process, the dependence of the material response on packing and on strain rate, as well as the dissipation mechanisms characterizing the granular flow (frictional force chains and inelastic collisions) (Ceccato et al. 2017).

The main goal of the authors is in fact to propose a design approach for the sheltering structures by integrating the formula previously introduced by the authors for the maximum impact force with the information about the time evolution of the impact force, necessary to compute the impulse and for dynamic design of sheltering structure.

2 Numerical Model

The DEM numerical simulations are performed by employing the commercial software PFC3D 4.0 (Itasca, 2011). The model is analogous to that described in Calvetti et al. (2017). The model geometry is plotted Fig. 1, whereas the model mechanical properties are listed in Table 1. In order to reduce the computational cost, the triggering and propagation phases have not been simulated and the impacting mass has been generated just in front of the vertical wall with a prescribed geometry and initial conditions (Calvetti et al. 2017). The dry impacting mass is represented as an assembly of polydisperse spherical particles of unit weight γ_g. The particle size distribution is uniform and is defined by assigning the average grain diameter D and the ratio between the maximum and the minimum particle diameter D_{max}/D_{min}. The contact force is computed by employing a linear model along the normal direction and a linear model in series with a slider obeying the Coulomb failure criterion, along the tangential direction. The contact law is thus defined by specifying the values of normal and shear contact stiffnesses, k_n/D and k_s/D, respectively, and the interparticle friction coefficient μ_g (see Table 1). In order to reproduce the response of a real granular material with non-spherical particles, particles rotation is not allowed (Calvetti 2008). The geometry of the impacting mass is characterized by the length $L = 15$ m and height $h = 3$ m. The front of the sliding mass is assumed to be planar and inclined of an angle α. Different front angles raging between 40° and 90° have been considered. In order to impose plain strain conditions, the flow is confined between two smooth lateral walls. The flow width is equal to $8D$, in order to avoid boundary effects (Calvetti et al. 2017; Ceccato et al. 2017). The mass flows on a horizontal wall with friction μ_b. The obstacle is modelled as a vertical rigid and massless wall of height $H = 6$ m and friction coefficient μ_w.

At the instant of time just before the impact, the mass is characterized by a horizontal velocity $u_0 = 8$ m/s and porosity n_0 ranging between 0.4 and 0.65. When