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Relationships between rain and displacements of an active earthflow: a data driven approach by EPRMOGA

R. Vassallo*, A. Doglioni, G.M. Grimaldi*, C. Di Maio*, V. Simeone****

(*) University of Basilicata, Italy

(**) Technical University of Bari, Italy

Abstract

Inclinometer and piezometer measurements have been carried out since 2005 in a slow active earthflow in a clay shale formation of the Italian Southern Apennines. Previous studies outlined the main geometrical and kinematic features of the landslide and the pore pressure response to rainfall. Displacement rates seem to depend on the hydrological conditions as suggested by their seasonal variations. The availability of long time series of data, in some period recorded in *continuum*, allows the use of a data mining approach to evaluate the relations among displacement rates in different points of the landslide, and between displacement rates and rainfall. To define such relations, the evolutionary modelling technique EPRMOGA, based on a genetic algorithm, has been used in this paper. The results give a deeper insight into the landslide behaviour on one hand, and on the other show the reliability of the technique, also in building up management scenarios. In particular, they show that the landslide displacements in different points of the slip surface, characterized by different average velocities, are contemporary at the considered time resolution of 10 days. The obtained relations allow to quantify the displacement rate variations due to contemporary rainfall. The influence of past rainfall is shown to decrease exponentially with temporal distance. Furthermore, the EPRMOGA simulations seem to confirm that there are no other dominant causes, besides rainfall, responsible of displacement rate variations.

Keywords: landslide; displacement; rainfall; data driven model; EPRMOGA

1. Introduction

The displacement rates of active clayey landslides generally undergo seasonal variations associated to hydrological conditions (Leroueil et al. 1996; Leroueil 2001 among others). To evaluate the relations among displacements, pore pressures and rain, several different approaches are reported in the technical literature which can be grouped into "physically based" and "phenomenologically based" (Cascini and Versace 1986). The former try to reproduce the physical processes of the system under study, the latter aim finding empirical correlations between the landslide displacements and their triggering factors, or statistical relationships between the measured groundwater pressures and rainfall, without explicitly considering the physical processes occurring in the slope.

Data-driven models are purely mathematical relationships among the variables of a physical system which are not based on a physical analysis. They thus can be ascribed to the group of "phenomenologically based" models. The types of input and output data are obviously selected starting from a general physical knowledge of the phenomenon under study, and the relationships among them are achieved by a trial and error strategy or by an adaptive automatic procedure. Such models can suitably be applied when long time series of monitoring data, such as inclinometer displacements, piezometric levels and rainfall heights, are available.

In this paper, the data driven evolutionary modelling technique EPRMOGA (Giustolisi and Savic 2009) is used to analyze the behaviour of the Costa della Gaveta earthflow, a slow active landslide, up to about 40 m deep, developing in a structurally complex clay shales formation of the Italian Southern Apennine. This earthflow is representative of a landslide typology widely diffused in Italy and also in all the Mediterranean area (Picarelli et al. 2000). Its displacements and pore pressures are being monitored since 2005 (Di Maio et al. 2010, Calcaterra et al. 2012, Vassallo et al. 2015), often with fixed in place instruments so that data driven analyses are possible. EPRMOGA already proved effective to model the dynamics of environmental systems in several cases, providing information on aquifer levels and landslide displacements (Doglioni et al. 2014; Doglioni et al. 2012; Doglioni et al. 2010; Giustolisi et al. 2008). The main advantage of this procedure is that it provides closed-form equations, characterized by relatively simple structures, that can be used both to forecast the landslide behaviour and to obtain more information about the landslide through a physical interpretation of the different terms of the equations.

For the case of Costa della Gaveta earthflow, the study has been carried out with the two aims of verifying the capability of the proposed mathematical technique in the evaluation of the relations among the involved physical parameters, for risk management and forecasting purposes, and achieving a deeper insight in the behaviour of an active clayey landslide. In particular, EPRMOGA has been used to evaluate the correlations among the displacement rates in different boreholes, between pore pressures and rainfall, and between displacements and rainfall. The absence of a relation between displacements and pore pressures in single points has been justified on the basis of previous studies (Vassallo et al., 2015) which show that the soil properties and landslide geometry are such that the pore water response to rainfall is characterised by noticeable depth-depending time lags. On the contrary, the displacement rates determined by different inclinometers on the slip surface at different depths are well correlated to one another and seem to depend on the overall pore water response of the landslide.

2. Costa della Gaveta landslide

Costa della Gaveta landslide is an active slow earthflow of the Southern Italian Apennines. It is about 1250 m long, from 100 to 600 m wide, with an average inclination of about 10° (Fig. 1). It is characterized by a maximum depth of about 40 m, a wide source area, mostly emptied, a straight channel and a large accumulation area. The material in the channel moves slowly or extremely slowly (Cruden and Varnes 1996), with displacement rates decreasing in the downslope direction.

The landslide occurs in two different geological formations: Varicoloured Clays and Corleto Perticara. Varicoloured Clays are constituted by an irregular alternation of thin beds of clays, marly clays and clayey marls. Corleto Perticara formation is constituted by an irregular succession of calcareous marls, marly limestones, white-grey calcilutites and, in the Costa della Gaveta zone, by frequent grey-brown clay layers up to about some meters thick.

The earthflow body, mainly constituted by destructured clays with abundant rock fragments, rather inhomogeneous, is characterized by a clay fraction *c.f.* up to 50% and liquid limit w_L between 40% and 80%. Below the first 2 m, the degree of saturation S_r can be considered equal to 100 %. An average residual friction angle φ'_r of about 10° was determined by laboratory tests (Di Maio et al. 2013, Di Maio et al. 2015).

Displacements are being monitored since 2005 in several verticals by inclinometers (Fig. 1) and a long rainfall time series is available. Pore pressures measurements are also available. Periods and frequency of measurement, and instrument accuracy, are reported in Table 1.

Displacement profiles have been obtained by frequent inclinometer measurements during the 10 years monitoring. A slip surface with a depth up to 40 m in the transition zone between the channel and the accumulation zone was detected (Fig. 2). In some boreholes, once the depth of the slip surface had been detected, fixed-in-place inclinometer probes with continuous data acquisition were installed.

Along the slip surface, the displacements occur with very different rates, decreasing in the downslope direction (Fig.3a), however they seem to be strongly correlated to each other in the whole monitoring period. Di Maio et al. (2010) and Di Maio et al. (2013) showed that such correlation is justified by a mechanism of constant soil discharge through the landslide channel. In fact, during the monitoring period, the same soil discharge (estimated by displacement rates and landslide cross section areas) is observed in different cross sections at the same time. The correlation can be better appreciated in Fig. 3b in which all the time series overlap by simply dividing each of them by a constant. Fig. 4 reports the displacement rates (divided by the same constants as in Fig. 3b), which for I9, I9b and I12 were also evaluated by fixed-in-place inclinometer measurements over about two years. Such rates, evaluated as 15 days-moving averages, agree with those of periodical manual measurements. The figure shows seasonal variations which can be reasonably attributed to the hydrological regime of the site.

The hydrological regime of the area is characterized by rainfalls of long duration and low medium intensity; short rainfalls of high intensity are quite rare. As typical of Italian peninsula, more than 60% of the total yearly rain falls during autumn and winter. The long historical rainfall series is characterized by a substantial uniformity over the years, as shown by Fig. 5a which reports the yearly cumulative rainfall from 1980 to 2015. The rainfall relative to the monitoring period (2005-2015) can be considered representative of the longer period (Fig. 5b).

Pore pressures were monitored by means of some electric and Casagrande piezometers at 15 m and 30 m depths, whose location is shown in Fig.1. The Casagrande piezometers were also used for the evaluation of the hydraulic conductivity k of the different formations of the subsoil (Fig.1). By falling head tests, values of k in the range 10^{-9} m/s - 10^{-8} m/s were evaluated in the landslide body, about 10^{-10} m/s in the stable Varicolured Clays, and 10^{-7} m/s in the Corleto Perticara formation. Vassallo et al. (2015) reported the results of a transient simulation, by the 3D finite difference code MODFLOW, of pore pressure response to a historical rainfall. A simulation with daily resolution succeeded in reproducing accurately an electrical piezometer data (S3, whose position is shown in Fig. 1) over the two years of continuous monitoring. The results of such analysis were thus used to interpret the landslide pore water pressure response to rainfall. The results show that: i) the response to rain along the slip surface is characterised by noticeable depth-depending time lags, and ii) pore water pressure variations induced by rainfall are significant only at depths lower than about 10 m. On the other hand, the displacement rates determined by different inclinometers on the slip surface are well correlated to one another: the landslide apparently moves with a constant soil discharge in the channel (Di Maio et al. 2010), whose trend seems very close to that of the average pore water pressure on the slip surface. The displacement rates on the slip surface are thus not correlated to pore water pressures in single points, i.e. to any single piezometer data.

3. EPRMOGA: assumptions and procedures

The availability of long time series of displacements, pore pressures and rainfall allows the use of the EPRMOGA data mining approach. This technique is a data-driven multi-objective evolutionary modelling technique (Giustolisi and Savic 2009), which proves particularly effective at modelling environmental phenomena characterized by high non-linearity, even with poor *a-priori* knowledge about their dynamics (Doglioni and Simeone 2014). It does not require pre-assumed equations governing the phenomenon under investigation. It does not need the calibration of physical parameters, and is particularly serviceable for managing purposes. Furthermore, a critical analysis of the relationships provided by EPRMOGA between input and output data can give an insight into the physics of the system even in the case of nonlinear processes.

The procedure is composed of two stages: *a)* identification of the model structure based on a genetic algorithm (Goldberg 1989; Giustolisi et al. 2004), *b)* estimation of the coefficients, based on a least-square approach. Assumptions are done on: structures of the equations, potentially involved functions, maximum length of the polynomial, exponents and objective functions, so as to set a limit to the evolutionary search, i.e. to the space of solutions. During the search for the equations, EPRMOGA can simultaneously minimize: a) the sum of squared errors, b) the number of terms, and c) the number of input variables. In this sense the approach is multi-objective, as three conflicting functions are simultaneously optimized. This allows to optimize the fit of the model to input data and to obtain simple structures that can be potentially interpreted. As a result, a set of solutions is provided, known as Pareto set (Pareto, 1896), which represents the trade-off among the three objective functions. None of the solutions can thus be considered the best among the others. In this way, EPRMOGA allows to compare the equations of the Pareto set and then to make a more robust choice of the equation, on the basis of both structure and involved variables. The choice is based on a compromise between the fit to experimental data and the structural parsimony of equations allowing a physical interpretation of the terms.

In this study, EPRMOGA is used to evaluate the correlation:

a) among the displacement rates in different boreholes;

b) between pore pressures and rainfall;

c) between displacements and rainfall.

EPRMOGA did not find direct relations between displacements and pore pressures measured at a specific depth, consistently with the results of Vassallo et al. (2015) recalled in the previous section.

Used input data are: average deep displacement rates over 10 days intervals, pressure head values extracted from the data series every 10 days, and cumulative rainfall heights over 10 days. This time interval allows a quite good resolution and a sufficient numerosity of data series. Given the very low displacement rates, a higher time resolution would be much affected by measurement uncertainty.

The model structure is assumed to be polynomial and the variables involved by each term, as well as the number of terms, are identified by EPRMOGA. Only positive terms have been considered since negative ones, for the studied phenomenon, would be purely interpolative, without physical soundness. Values of the variables at several different times can be assigned as input to the models. For example, in the analysis of the relations displacement rates vs. rainfall, the assumed candidate pool of variables includes: v_{t-1} and v_{t-2}, i.e. displacement rates at 10 days and 20 days before the output, and P_t, P_{t-1}, P_{t-2}, P_{t-3}, P_{t-4}, P_{t-5}, P_{t-6}, i.e. rainfall ranging from contemporary to 60 days before. To limit the complexity of the models, the exponents of the variables are assumed to be either 0, 1 (linear relationship), 0.5 (attenuation) or 2 (amplification). Each provided model is the outcome of an optimization aimed at the structural parsimony as well as at the maximization of the fitness to measured data. This is why not all the variables are expected to appear in the models.

Similarly, as far as the relationship pore pressures vs. rainfall is concerned, variables include u_{t-1} and u_{t-2}, i.e. pore pressures at 10 and 20 days before the output, and rainfall P_t, P_{t-1}, P_{t-2}, P_{t-3}, P_{t-4}, P_{t-5}, P_{t-6} from contemporary to 60 days before.

The fitness of model output to measured data is evaluated by the Coefficient of Determination (CoD):

$$\boldsymbol{CoD} = 1 - \frac{\boldsymbol{N}-1}{\boldsymbol{N}} \frac{\sum_N \left(\boldsymbol{v}_{EPR} - \boldsymbol{v}_{\exp}\right)^2}{\sum_N \left[\boldsymbol{v}_{\exp} - \boldsymbol{avg}(\boldsymbol{v}_{\exp})\right]^2} \quad (1)$$

where N is the number of samples, v_{EPR} and $v_{\exp}$ are displacement rates, respectively returned by EPRMOGA and measured, and avg($v_{\exp}$) is the average of $v_{\exp}$ values. The closer to 1 is the CoD, the better is the model simulation of measured data.

The comparison of the models obtained by EPRMOGA and the experimental data can be carried out in two different ways, to predict displacements or pore pressures over the whole studied period (this mode is called “simulation” in the following), or over only some time steps ahead (this mode is called “prediction” in the following). In the simulation over the whole period of interest, once the initial condition is defined, the past values of displacement rate or pore pressure are recursively estimated by the model itself. In other words, given the rainfall values, the model becomes completely determined. Differently, in the prediction over a shorter period, the estimation of the previous values by the model is periodically substituted by the experimental data. Thus the model is periodically set out to reality. If the results of simulation agree with those of measurements, then the general behaviour of the system was caught. The difference between measured and calculated values may be locally different for several reasons, but if measured and simulated values do not diverge in the long period it means that the model is able to simulate the system general behaviour. Local differences may be due to several reason, such as measurement errors or influence of extra-input not considered in the analysis.

4. EPRMOGA: results

The EPRMOGA equations of displacement rates have been evaluated for inclinometers I9b and I9c, located in the same transversal section of the channel, and I12, located at the head of the landslide body (Figs. 1 and 2) because of the availability, in such verticals, of continuous data for some years and for their higher velocity. The location of inclinometers I9b and I9c was chosen so as to study the velocity distribution in ~~deformation of~~ a transversal section. Inclinometer measurements in I7, in the lower part of the landslide, have not been used due to the very low velocities (about 1 mm/year). Data relative to I8, recorded with lower frequency by manual measurements (Tab. 1), have not been used to determine a model but have been analyzed by the equations found for the other boreholes.

For pore pressures analyses, the results relative to the electric piezometer S3 with continuous data acquisition will be used. Such piezometer is located in the nearby Varco D’Izzo landslide (Fig. 1), which develops in the same materials as Costa della Gaveta landslide, and is the only electric piezometer in the studied zone which provided continuous data for a period of two years without interruptions. Vassallo et al. (2015) showed that its data can be considered representative of the pore pressure response in Costa della Gaveta. They also reported measurements of the electric piezometer S9 located in Costa della Gaveta landlside (Fig. 1) showing that, in the few months in which it was in use, it provided pressure values comparable to those measured by S3 at the same depth.

For each analysis, a Pareto set of equations is identified. Then, among these, one equation will be chosen, according to the above mentioned criterions.

4.1 Relationships among displacement rates of inclinometers located in different positions of the landslide profile

The analysis has been performed over the period November 2012 - May 2015 during which data have been obtained by fixed in place probes. Data obtained before then have not been used since manual inclinometer measurements had been carried out with a frequency lower than that required by the analysis, that is 1/10days.

The relationships among the deep displacement rates in I9b, I9c, and I12 has been sought, for each couple of inclinometers, also switching the dependent and independent variables. The selected equations, plotted in Figs. 6-8, are the following:

$$\boldsymbol{v}_t^{\boldsymbol{I9b}} = 0.243\boldsymbol{v}_t^{\boldsymbol{I}12} + \left(0.010 \text{ cm/10days}\right) \quad (2)$$

$$\boldsymbol{v}_t^{12} = 2.692\boldsymbol{v}_t^{\boldsymbol{I9b}} \quad (2')$$

$$\boldsymbol{v}_t^{\boldsymbol{I9b}} = 0.849\boldsymbol{v}_t^{\boldsymbol{I9c}} + \left(0.011 \text{ cm/10days}\right) \quad (3)$$

$$\boldsymbol{v}_t^{\boldsymbol{I9c}} = 0.723\boldsymbol{v}_t^{\boldsymbol{I9b}} \quad (3')$$

$$\boldsymbol{v}_t^{\boldsymbol{I9c}} = 0.220\boldsymbol{v}_t^{\boldsymbol{I}12} + (0.004 \text{ cm/10days}) \quad (4)$$

$$\boldsymbol{v}_t^{\boldsymbol{I}12} = 1.793 \cdot \sqrt{\boldsymbol{v}_{t-1}^{\boldsymbol{I}12} \cdot \boldsymbol{v}_t^{\boldsymbol{I9c}}} + (0.007 \text{ cm/10days}) \quad (4')$$

Figs. 6, 7 and 8, that compare experimental data to those simulated by the above equations, show a satisfactory model performance. CoD values, reported in the figures, confirm that equations (2) and (2’) provide a good agreement between measured and model-returned displacement rates. Equations (3), (3’) and (4) have still a rather good performance. The correlation becomes worse for eq. (4’) (I12 vs I9c) but is still able to reproduce the general behaviour of I12. For each couple of equations, the first one does not correspond to the second one inverted because it was *a priori* assumed that all the coefficients are positive.

With the exception of (4’), the equations relate contemporary displacement rates only, thus suggesting the simultaneity, under the considered time resolution, of displacements in correspondence of the different points of the landslide slip surface. Thus there seems to be no delayed propagation phenomenon appreciable at the used time scale. This agrees with the observation that the displacements of the different parts of the landslide are strongly correlated to one another as an effect of a constant soil discharge mechanism of movement in the channel (Di Maio et al. 2010). Furthermore, it can be observed that five out of six equations are linear and provide ratios between the velocities very close to those reported in Figs. 3b and 4.

It is worth noting that, with the exception of eq. (4'), the models do not contain the term of displacement rate at the previous time steps, thus EPRMOGA works just in simulation mode all over the considered period.

4.2. Relationships between pore pressures and rainfall

Pressure head (u/γ_w) variations recorded continuously by piezometer S3 (Fig. 1, Tab. 1) from 2005 to 2008 have been here analysed as a function of rainfall. The best fitting equation provided by EPRMOGA is:

$$\left(\frac{u}{\gamma_w}\right)_t = 0.0584 P_t^{0.5} + 0.032\left(\frac{u}{\gamma_w}\right)_{t-1}^2 + 7.233 \qquad (5)$$

with u/γ_w in m and rainfall in mm.

The equation is very simple and has a quite satisfactory performance in the simulation mode (Fig. 9). The first term of the equation, damped by the exponent 0.5, is representative of the response to contemporary rainfall. The second one is a "memory term" representative of the effect of the state of the system as determined by previous rainfall. The third term probably contains the effect of hydraulic conditions on boundaries different from the ground surface.

It is interesting to observe that the behaviour described by eq. (5) is very similar to that obtained by Vassallo et al. (2015), for the same piezometer, through the physically based Modflow 3D simulation. So the results of the two models, obtained using different approaches, are in good agreement, as clearly shown by Fig. 9, and very close to the experimental data.

Pore pressures measured by Casagrande piezometers were also used to evaluate the relationship between pressure head and rainfall. However, EPRMOGA did not find any relation. This agrees with the results of Vassallo et al. (2015) who showed that the Casagrande piezometers' data are characterized by noticeable time lag and lower sensitivity to individual rainfalls than the electric piezometer S3.

4.3. Relationships between displacement rates and rainfall

EPRMOGA returned equations of displacement rates vs. rainfall similar for the different inclinometers:

$$v_t^{I12} = 0.000787 \cdot P_t + 0.707 \cdot v_{t-1}^{I12} \qquad (6)$$

$$v_t^{I9b} = 2.590 \cdot 10^{-6} \cdot P_t^2 + 0.718 \cdot v_{t-1}^{I9b} + 0.004 \quad (7)$$

$$v_t^{I9c} = 2.453 \cdot 10^{-6} \cdot P_t^2 + 0.689 \cdot v_{t-1}^{I9c} + 0.002 \quad (8)$$

with displacement rates in cm/10days and rainfall in mm.

Figures 10, 11 and 12 report displacement rates evaluated over the whole considered period (November 2012 – June 2015), and of 40-days-ahead predictions, showing that there is no substantial improvement in the prediction compared to the simulation. The agreement with experimental data, with CoD ranging from 0.59 to 0.73, can be considered satisfactory.

The equations include a term of persistence, i.e. the velocity at the previous time step, that has an influence of about 70%, a term related to contemporary rainfall and a third term, constant, whose value is very close to zero. The above equations also imply that, in dry periods (P=0), displacement rate decreases by about 70% per time step, i.e. exponentially.

It is interesting to analyze in detail the persistence term. For example, eq. (6) can be re-written as:

$$v_t = a \cdot P_t + 0.71 v_{t-1} \quad (6')$$

and, applied in sequence for successive time steps, it becomes:

$$v_t = a \cdot P_t + 0.71 \cdot \left(aP_{t-1} + 0.71 v_{t-2}\right) = a \cdot \left[P_t + 0.71 P_{t-1} + 0.71 \cdot \left(aP_{t-2} + 0.71 v_{t-3}\right)\right] =$$

$$= a\left(\sum_{i=0}^{n-1} 0.71^i P_{t-i} \ldots\right) + 0.71^n v_{t-n} \quad (6'')$$

which can be approximated by neglecting the last term and considering just a few P_{t-i} terms. For example, by considering 7 terms we obtain:

$$v_t \cong a \cdot \left(P_t + 0.71 P_{t-1} + 0.71^2 P_{t-2} + 0.71^3 P_{t-3} + 0.71^4 P_{t-4} + 0.71^5 P_{t-5} + 0.71^6 P_{t-6}\right) \quad (6''')$$

which explicitly expresses the dependency of displacement rate on past rainfall. Fig. 13 shows that even just the first 5 terms of eq. (6'') reproduce very accurately the trend of eq. (6).

Equation (6), which relates the displacement rate of I12 (installed in august 2012) to rainfall, calibrated in the period 2013-2015, was used to evaluate the displacements which could have occurred in the same location in the eight years before (2005-2013) during which other inclinometers were in use. Fig. 14 shows that the calculated values of I12 agree with the experimental data of the other inclinometers (I10, I9, I8) if each data series is multiplied by a constant. The used values of constants are the same as those reported in Fig. 4. Among other things, this suggests that there are not other dominant causes, besides rainfall, responsible of the landslide displacement rate variations. It seems thus reasonable to hypothesize that, in the absence of exceptional events, natural or anthropic, and for an unchanged hydrological regime, the next future behaviour of the landslide will not be different from the current one. Actually, on the basis of incoming climate changes, a modest decrease in the piezometric levels, and thus a decrease in the annual displacement, was hypothesized by Comegna et al. (2013). The Authors examined the potential changes in the pore water pressure of Costa della Gaveta slope in the next 50 years. For an inclinometer in the nearby Varco d'Izzo landslide (I3 in Fig.1), comparable to I12 for displacement rates and slip surface depth, they evaluated an average decrease between 1.5 and 3 mm/decade per decade, depending on the climate scenario, with phases of moderate acceleration during winter and spring. The rate decrease is negligible, since a substantially linear trend in average yearly cumulative displacements was obtained.

5. CONCLUSIONS

The Costa della Gaveta earthflow is a slow active landslide which occurs in a structurally complex clay shales formation of the Italian Southern Apennine. Its displacements and pore pressures are being monitored since 2005, often with fixed in place instruments. In this paper, the relationships among displacements, pore pressures and rainfall has been sought through an evolutionary modelling data driven technique called EPRMOGA, based on a genetic algorithm. Its main advantage is that it provides closed-form equations, with the different terms characterized by relatively simple structures, so that the physical interpretation of the phenomenon under examination can be attempted.

The study has allowed to achieve a deeper insight in the behaviour of a widely diffused type of landslide.

The results show that the landslide displacements in different points of the slip surface are contemporary at the considered time resolution (10 days), consistently with the hypothesis by Di Maio et al. (2010) of constant soil discharge in the landslide channel. The relation found between pore pressures and rainfall is able to reproduce quite accurately the experimental data and also the results of a physically based 3D model (MODFLOW). The obtained relations allow to quantify the displacement rate variations due to contemporary rainfall and the influence of past rainfall, which decreases exponentially with temporal distance. Furthermore, EPRMOGA simulations suggest that there are no other dominant causes, besides rainfall, responsible of the landslide displacement rate variations.

Finally, the study has shown the reliability of EPRMOGA in the evaluation of the relations among the physical parameters involved in the behaviour of active landslides belonging to the same typology of the considered one, even for management and forecasting purposes.

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Table 1. Type, periods and frequency of measurements. Instrument accuracy is: ± 6mm/25m for manual inclinometer probe; ± 15mm/25m for fixed in place probe; ±2 kPa for electric piezometer. Manual inclinometer measurements were performed at 0.5 m intervals by a 0.5 m long probe. In correspondence of the slip surface, some measurements were carried out 10 cm intervals. Inclinometer measurements were validated by spiral correction and by performing periodical measurements in all the grooves ("A" and "B") of the inclinometer casings. Azimuth was always checked. First months of measurements were excluded from results.

Inclinometer	**Type of measurement**	**Operational period**	**Reading frequency (t^{-1})**	**Cause of interruption**
I8	manual	Mar 2005 – Nov 2013	1/(1 month)	inclinometer tube sheared off
I9	manual	Mar 2005 - Jul 2006 -------------------- Feb 2010 - Feb 2012	1/(1 month) -------------------- 1/(1 month)	installation of fixed in place probe --------------------- inclinometer tube sheared off
	fixed in place probe	Jul 2006 – Jan 2009	1/(2 hrs)	electric malfunctioning probably due to corrosion of cables
I10	manual	Mar 2005 – Dec 2007	1/(1 month)	inclinometer tube sheared off
I9b	manual	Mar 2012 – May 2014	1/(1-2 weeks)	installation of fixed in place probe
	fixed in place probe	May 2014 - present	1/(2 hrs)	-
I9c	manual	Jan 2013 - present	1/(1-2 weeks)	-
I12	manual	Jul 2012 - Feb 2014	1/(1-2 weeks)	installation of fixed in place probe
	fixed in place probe	Feb 2014 – present	1/(2 hrs)	-
Piezometer	**Type of measurement**	**Operational period**	**Reading frequency**	**Cause of interruption**
S3 (depth: 14.5 m)	electric	Mar 2005 – Oct 2008	1/(2 hrs)	electric malfunctioning probably due to corrosion of cables

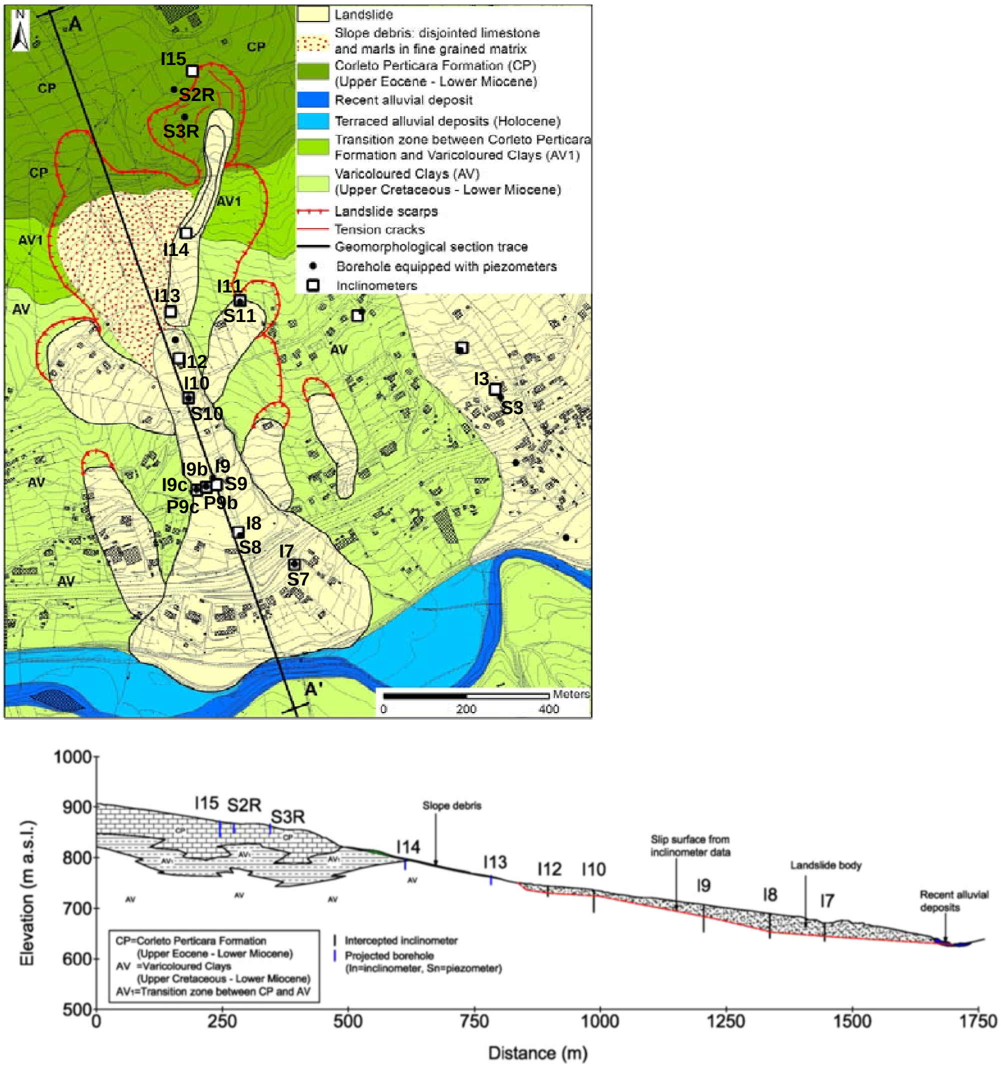

Fig. 1. *Costa della Gaveta landslide with the localization of piezometers (S, P) and inclinometer casings (I): geological map and section (after Vassallo et al. 2014).*

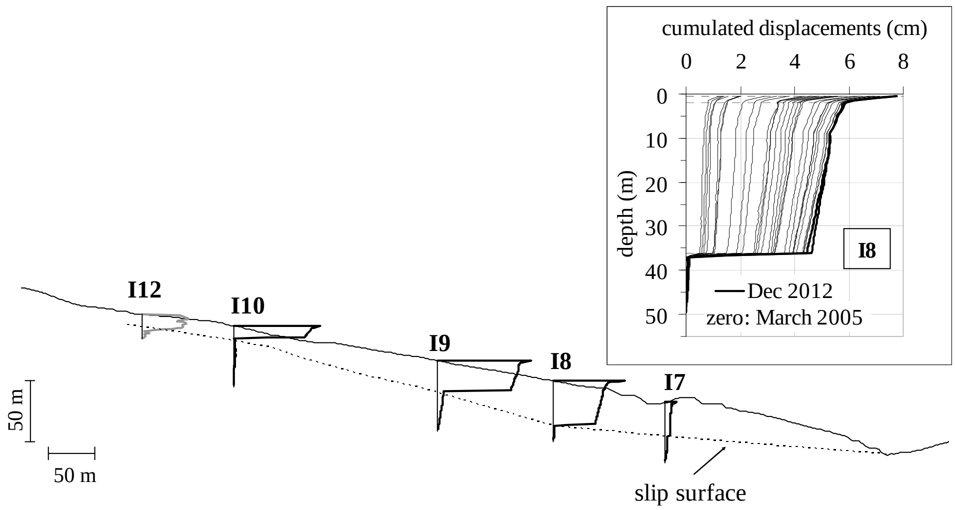

Fig. 2. *Longitudinal median section of the earthflow with inclinometer profiles.*

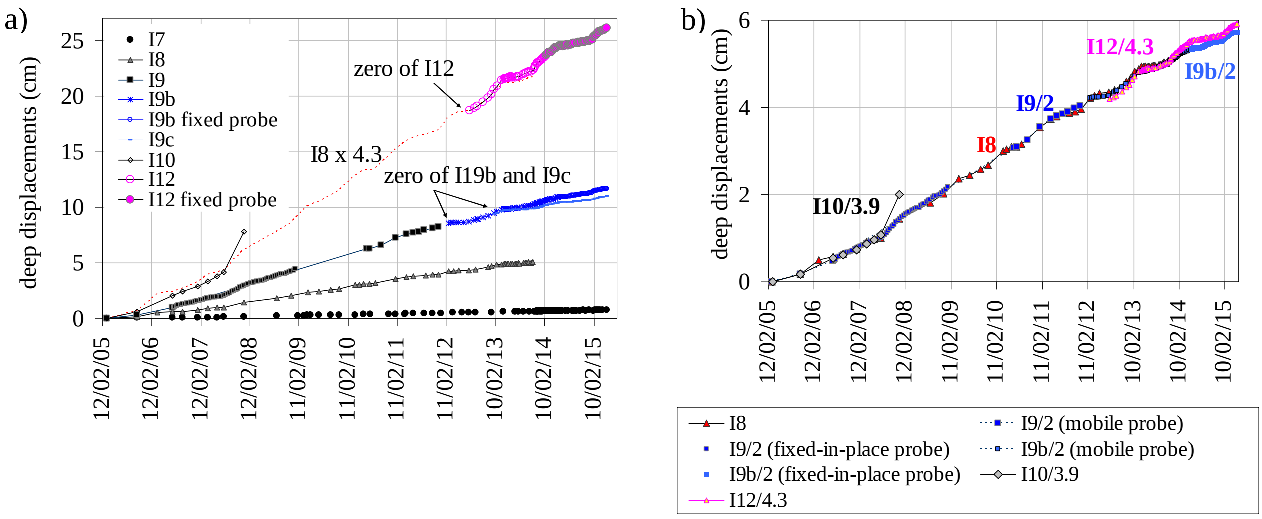

***Fig. 3.** Relative displacements on the slip surface against time: a) measured; b) scaled with reference to I8 time-trend (update of the results reported by Di Maio et al. 2013).*

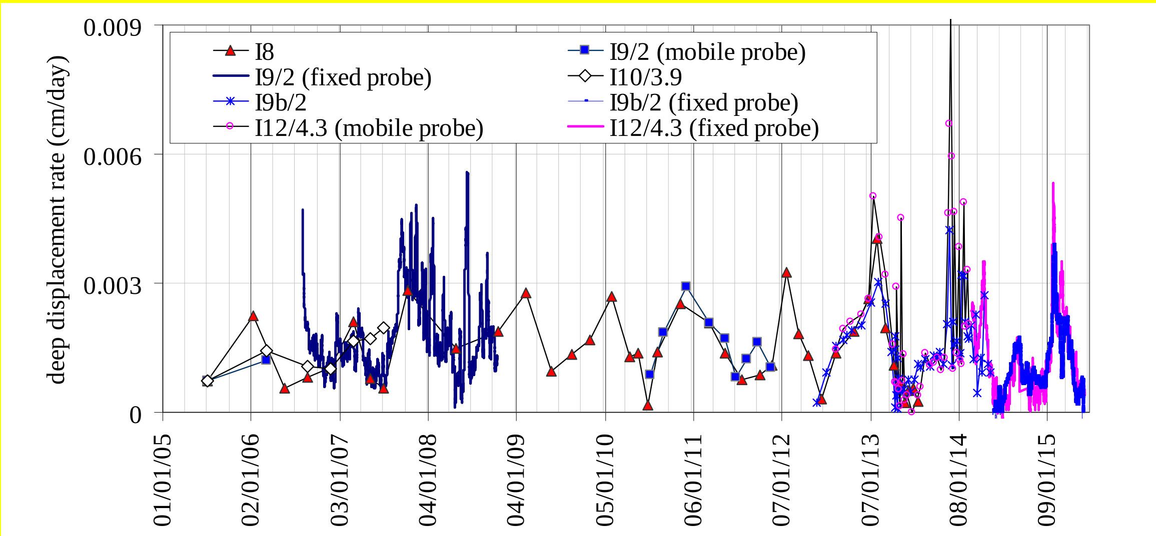

***Fig. 4.** Displacement rate on the shear surface obtained from fixed-in-place inclinometer measurements by using 15 days moving average and from mobile inclinometer measurements. Data series of every inclinometer was scaled with reference to I8 time-trend.*

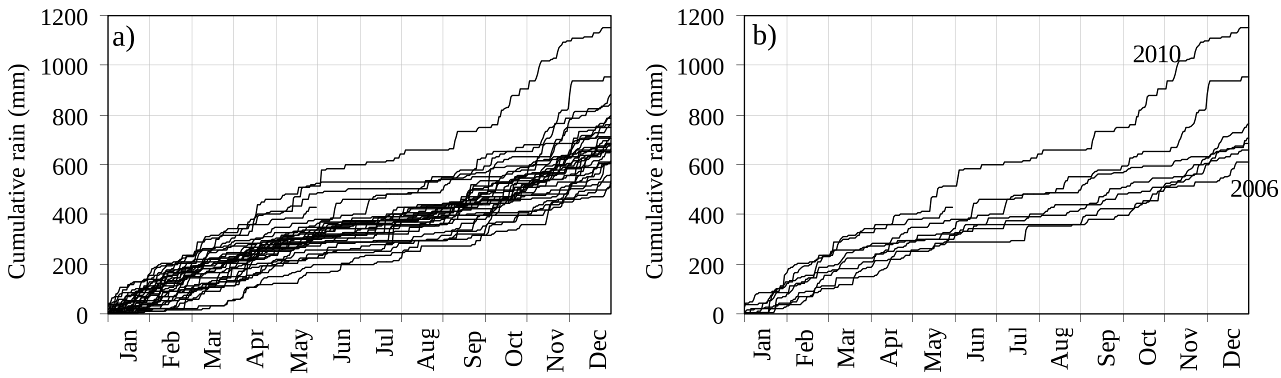

***Fig. 5.** Cumulative rainfall series: a) over years 1980-2015; b) over the period of monitoring, 2005-2015.*

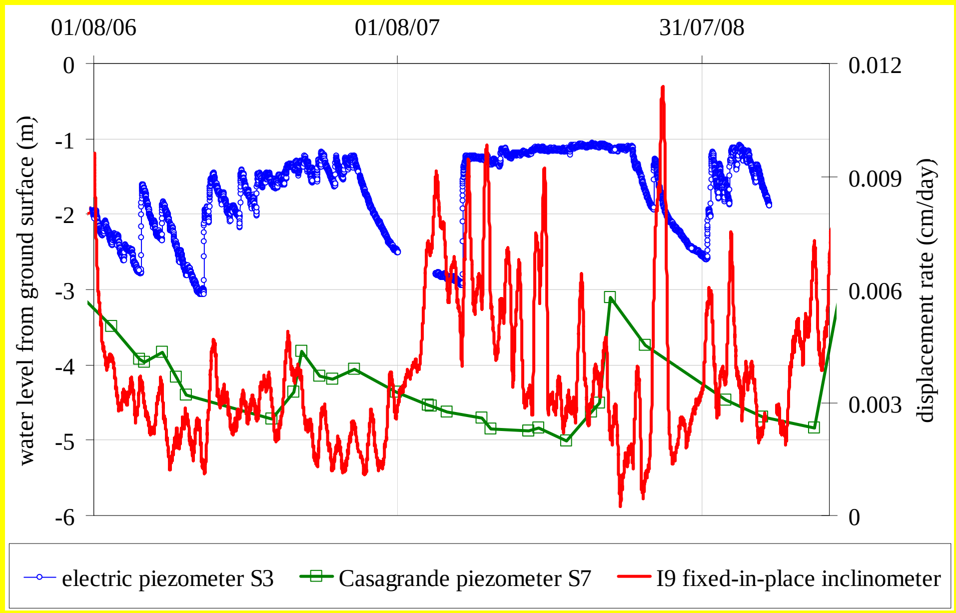

Fig. 6: *Comparison of the time trends of displacement rates measured in inclinometer I9 and of water level from the ground surface measured in piezometers S3 and S7.*

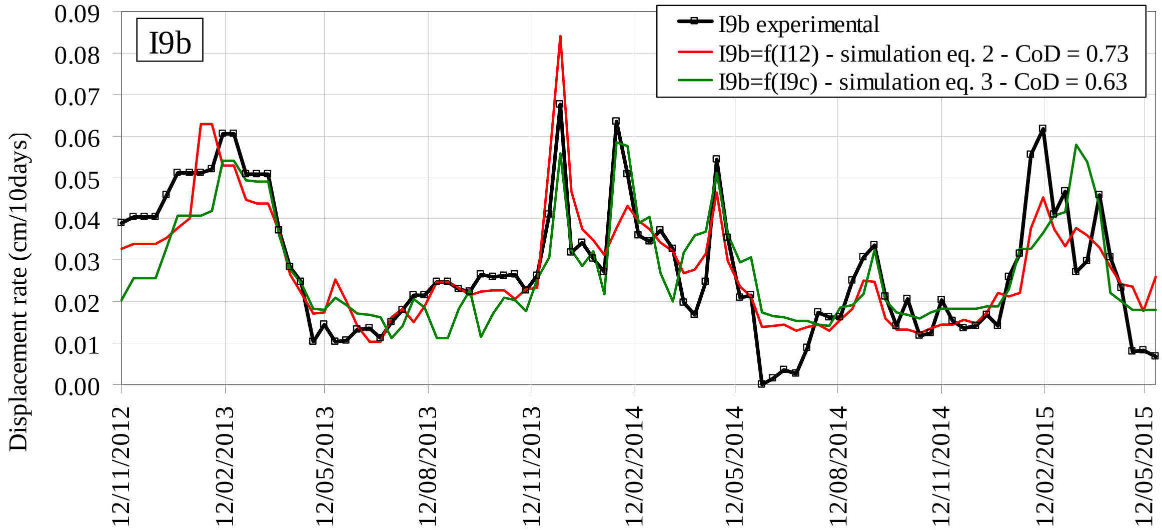

Fig. 7: *Time plot of displacement rates measured in situ in I9b and calculated by equation (2), I9b vs. I12, and (3), I9b vs. I9c.*

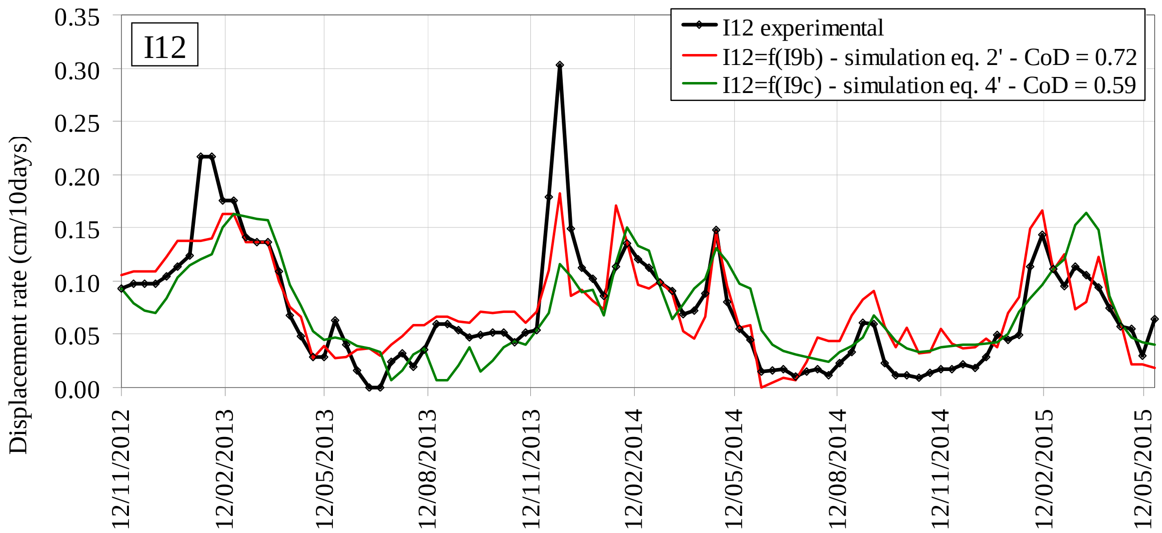

Fig. 8*: Time plot of displacement rates measured in situ in I12 and calculated by equation (2'), I12 vs. I9b, and (4'), I12 vs. I9c.*

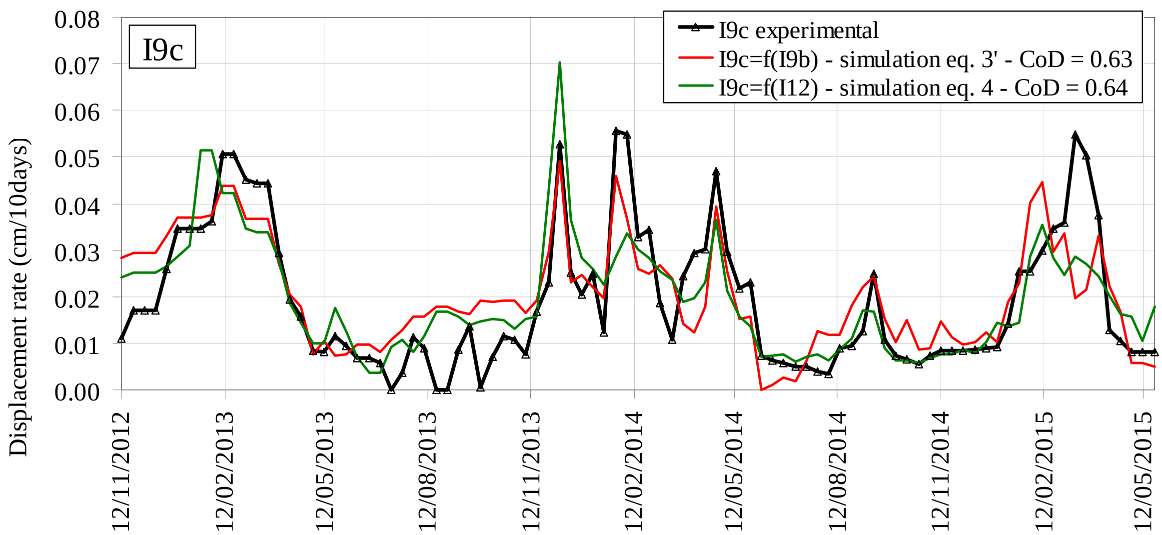

Fig. 9*: Time plot of displacement rates measured in situ in I9c and calculated by equation (3'), I9c vs. I9b, and (4), I9c vs. I12.*

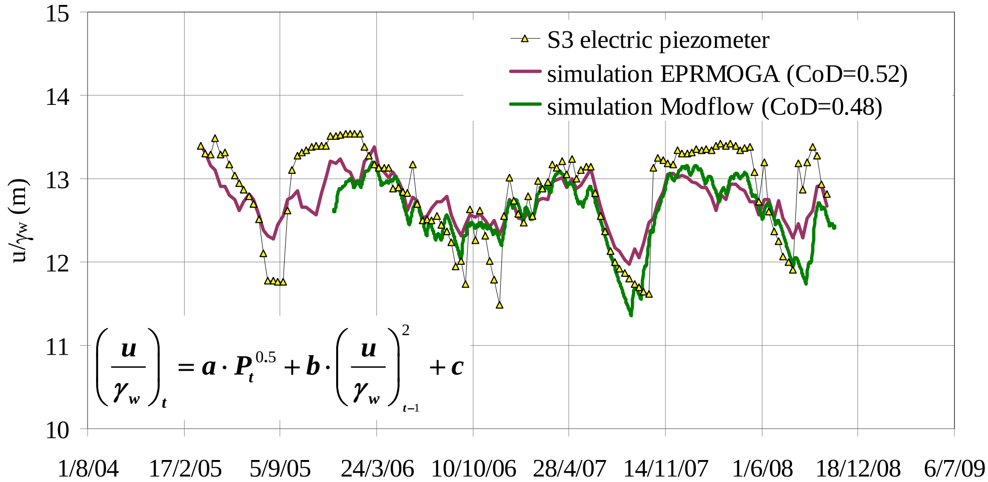

Fig. 10*: Time plots of pressure head u/γ_w measured by electric piezometer S3, calculated by equation (5), and obtained through the Modflow 3D transient simulation by Vassallo et al. (2014).*

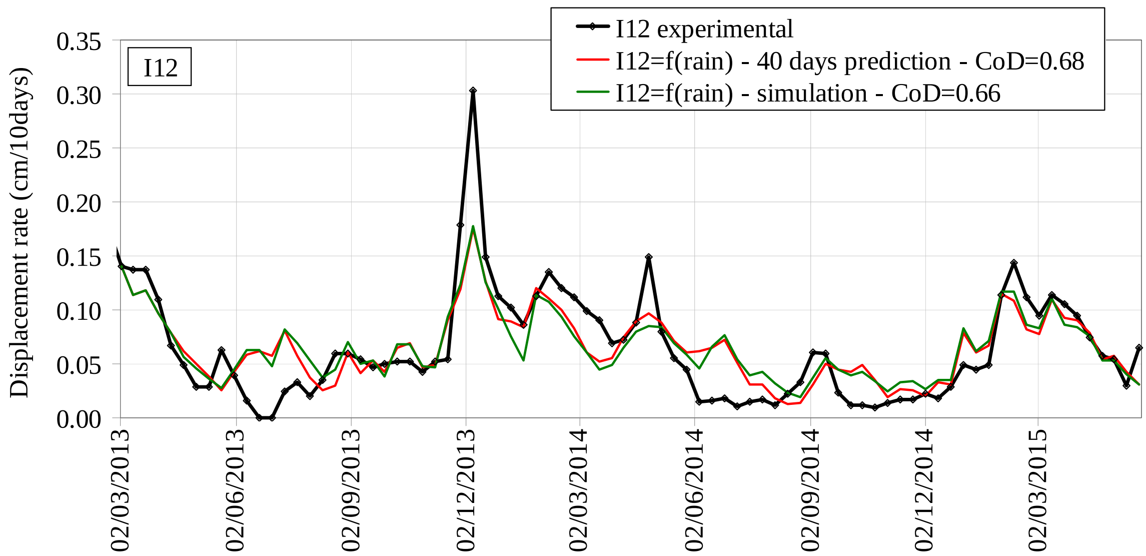

Fig. 11*: Time plot of displacement rates of I12: measured data, 40-days ahead prediction and simulation obtained by equation (6).*

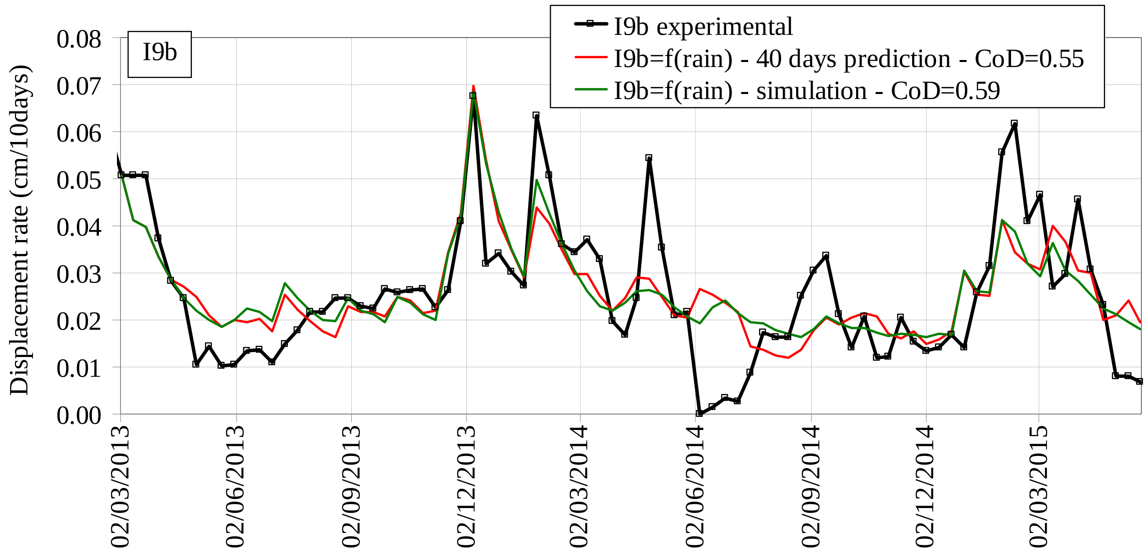

Fig. 12*: Time plot of displacement rates of I9b: measured data, 40-days ahead prediction and simulation obtained by equation (7).*

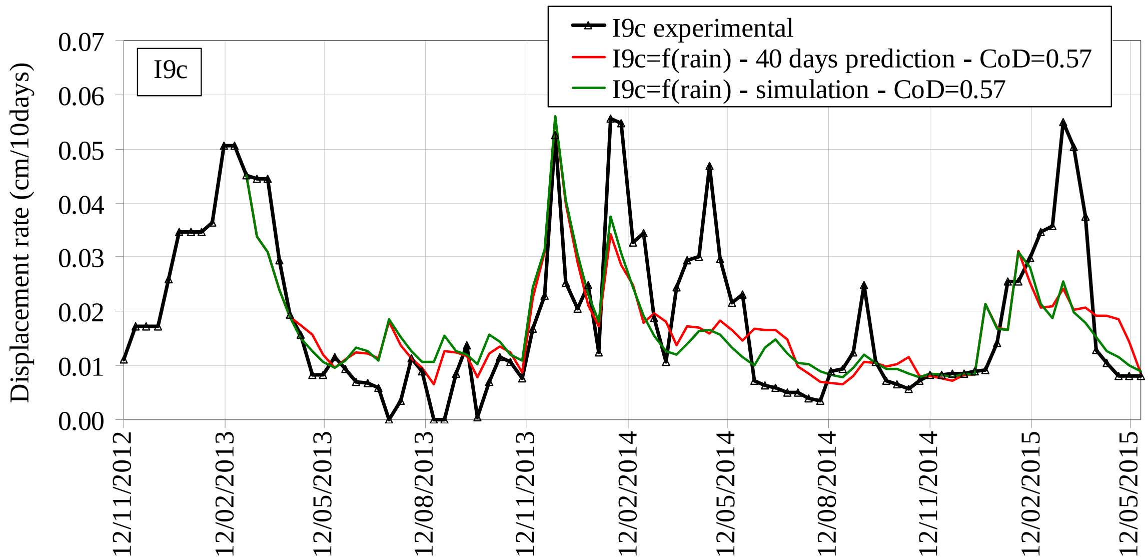

Fig. 13*: Time plot of displacement rates of I9c: measured data, 40-days ahead prediction and simulation obtained by equation (8).*

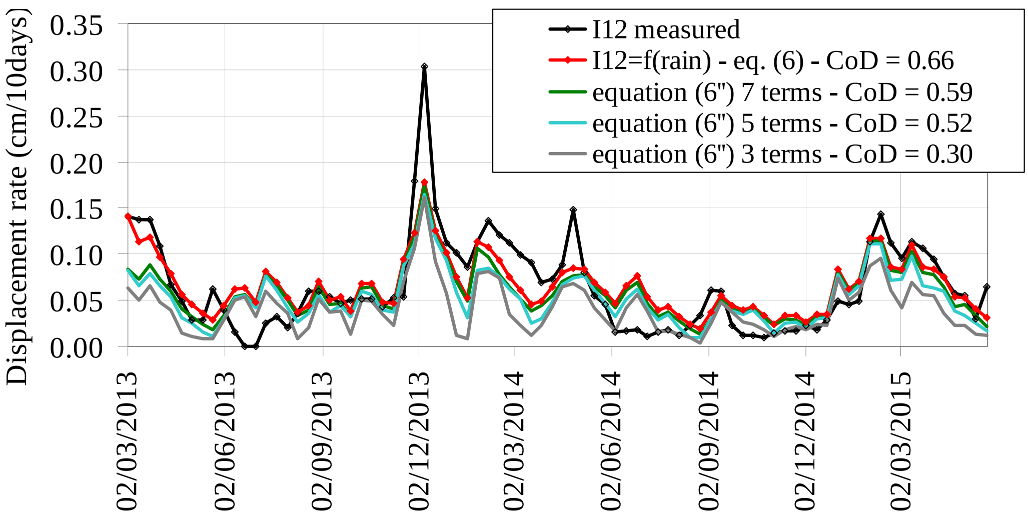

***Fig. 14**: Time plot of displacement rates measured in I12 compared to those obtained by equation (6) and by equation (6'') considering all its seven terms or just the first 5 or the first 3.*

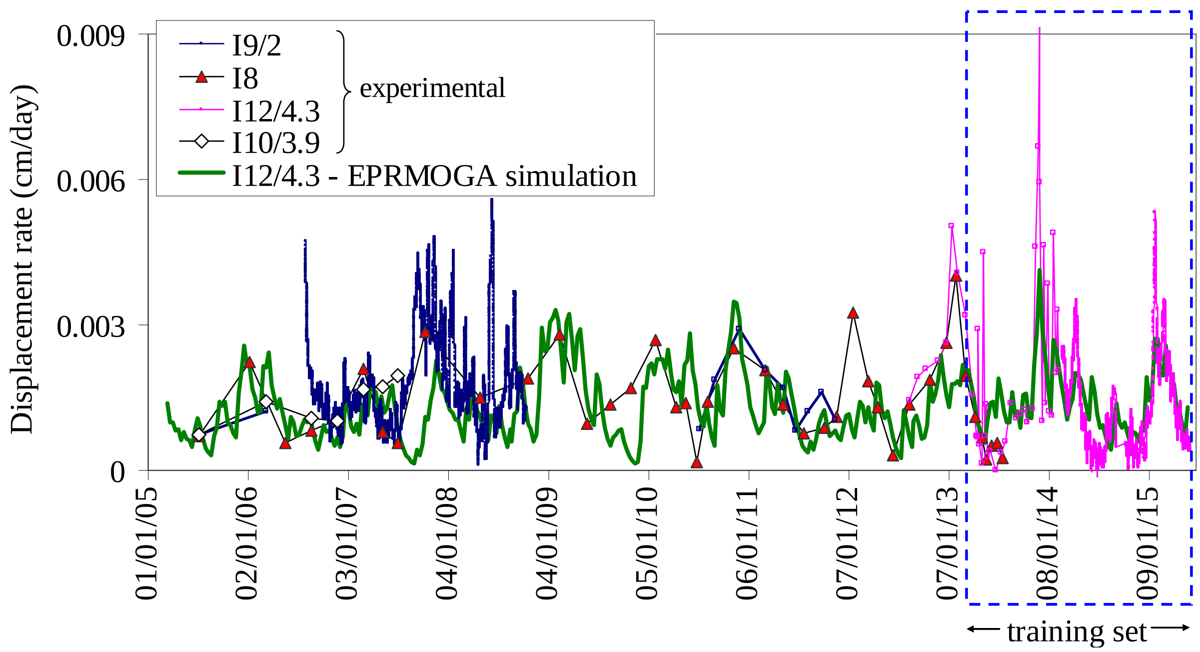

***Fig. 15**: Comparison between EPRMOGA simulation over the whole monitoring period 2005-20015 and measured displacement rates in different points of the landslide. The simulation was calibrated on the experimental data of inclinometer I12 in the period 2013-2015.*