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# Forewarning model for landslides triggered by rainfall based on the analysis of historical data file

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**Abstract** Landslides triggered by rainfall could be forecast by modelling the relationship existing between landslide occurrences and antecedent precipitation events. The FLaIR hydrological model allows the forecast through the joint employment of two modules: RL (Rainfall-Landslide) and RF (Rainfall Forecasting). The first module identifies the relationship between rainfalls and landslides by means of a "mobility function" $Y(t)$, obtained through the convolution of the infiltrated rainfalls and a "transfer function" $\psi(t)$. The second module uses stochastic models of rainfall for a probabilistic assessment of the mobility function evolution. In the present paper a selected group of case-studies, referred to Italian territory, has been analysed in order to test the performances of the FLaIR model for landslides with different characteristics. The applications underline a similarity of the estimated transfer functions for landslides with similar lithological characteristics. This result could be very useful in landslide forecasting when there is a lack of data.

**Key words** civil protection; hydrological model; Italian territory; landslides-rainfalls

## INTRODUCTION

Several models have been suggested to analyse landslide mobilizations when the triggering process is essentially governed by rainfalls (Campbell, 1975; Au, 1993; Sandersen *et al.*, 1996; etc.). One category of these models, called hydrological models, are simply based on a description of the links between the antecedent rainfalls and the time of slide movement. Application of hydrological models, usually, requires that the landslide movements exhibit a stationary behaviour and then that no structural modifications, due to human activity or natural causes, exist on the hillslope. Among such models, the FLaIR model (Forecasting of Landslides Induced by Rainfall), proposed by Sirangelo & Versace (1992), will be employed here. In the following paragraphs, after a brief description of the FLaIR model, its application to different cases are presented.

## FLaIR MODEL

The FLaIR model is applicable to landslides, triggered by rainfall, with repeated movements under the hypothesis of stationary behaviour. The model contains two modules. The first one is the RL (Rainfall-Landslide) module, that links the probability $P[E_t]$ of movement at the time $t$ to the value of a mobility function, $Y(t)$, depending on the rain fallen before the time $t$, through the simple relationship:

$$P[E_t] = \begin{cases} 0 & if \quad Y(t) \le Y_{cr} \\ 1 & if \quad Y(t) > Y_{cr} \end{cases} \tag{1}$$

where $Y_{cr}$ is the threshold value of the mobility function. The second module is the RF (Rainfall Forecasting) module that, through stochastic rainfall modelling, allows the simulation of future rainfall events.

The link between the mobility function and the antecedent rainfall is expressed by a convolution between the infiltration rate and a transfer function:

$$Y(t) = c \int_{-\infty}^{t} \psi(t-s) I(s)\,\mathrm{d}s \tag{2}$$

where $\psi(.)$ is the transfer function that takes into account the physical phenomena that transform the infiltration in the piezometric head of the subsoil aquifer at the landslide site, $I(.)$ is the infiltration rate and $c$ is a constant depending on the characteristics of the groundwater system. The careful choice of the transfer function permits the reproduction of many different situations that may occur in a slope, as shown in an extensive investigation developed by Sirangelo *et al.* (1996). A typical form of $\psi(.)$ is the *gamma* function:

$$\psi(u) = \frac{u^{\alpha-1}\exp(-u/\beta)}{\beta^{\alpha}\Gamma(\alpha)} \qquad u \ge 0; \quad \alpha > 0; \quad \beta > 0 \tag{3}$$

The parameter $\beta$ defines the temporal scale and the parameter $\alpha$ describes the hydrological response delay of the phenomenon with respect to the precipitations. It should be noted that in equation (2) the infiltration rate $I(.)$ appears, but the time series of such a hydrological quantity is normally not available. Infiltration must be derived from the rainfall time series. However, a detailed description of the transformation of total rainfall into infiltration rate cannot be implemented here since rainfall time series are usually only available on a daily scale. In these conditions it is suitable for the adoption of a very simple scheme in which the infiltration rate is considered proportional to the mean rainfall intensity if the total rainfall in the interval $\Delta t$ = 1 day is less than a value $h_0$ and, for total rainfall greater than $h_0$, the infiltration rate is assumed equal to $P_0 = h_0/\Delta t$:

$$I(\tau) = rP_*(\tau) \ \text{ with } \ P_*(\tau) = \begin{cases} P(\tau) & when \quad P(\tau) \le P_0 \\ P_0 & when \quad P(\tau) > P_0 \end{cases} \tag{4}$$

with $r$ being a factor of proportionality. The value $h_0$ is fixed, depending on the maximum capacity of the ground infiltration estimated on the basis of physical considerations of the nature of the soil.

Because the mobility function may be defined up to an arbitrary multiplicative factor, it is possible to set $r \cdot c = 1$, so that:

$$Y(t) = \int_{-\infty}^{t} \psi(t-s) P_*(s)\,\mathrm{d}s \tag{5}$$

The estimated parameters of the transfer function, α and β, must be able to ensure the condition for which the mobility function attains its highest values just in correspondence with the historical movements. The applications to real cases show that very often this condition is respected by more than one set of parameters and an admissibility field, instead of a single set of values, can be found for the parameters. Sirangelo *et al.* (1996) proposed two techniques, called ranking and crossing, for the identification of the parameter admissibility field. Referring to the original paper for more details and using the first technique, the parameter admissibility field can be bounded evaluating the mobility function $Y(t;\underline{\theta})$ on all the range of variability of the parameters $\underline{\theta}$ and retaining admissible all those values of $\underline{\theta}$ bringing $Y(t;\underline{\theta})$ to assume its $k$ highest values in correspondence with the $k$ historical movements of the landslide. $Y_{cr}$ is the lowest value of the mobility function among those assumed in correspondence with the $k$ historical movements, calculated on the basis of one representative parameter set selected inside the admissibility field.

For the purpose of real-time forecasting of movement probability it is useful to subdivide the mobility function in two components, deterministic and stochastic:

$$Y_\tau(t) = Y_\tau^{(\mathrm{det})}(t) + Y_\tau^{(\mathrm{sto})}(t) \qquad (6)$$

where $Y_\tau(t)$ indicates the estimation, at the time $t$, of the value of the mobility function at the time $t$. The term $Y_\tau^{(\mathrm{det})}(t)$ depends only on the rain fallen in the past and is, thus, known at the current time. On the contrary, the term $Y_\tau^{(\mathrm{sto})}(t)$ depends on the rain that will fall in the interval $[\tau,t]$. Equation (6) allows the definition of a confidence interval for the mobility function at the time $t$. Clearly, to assess such a confidence interval, a probabilistic description of the stochastic component is required. Contributions about this aspect can be found in the works of Iiritano *et al.*, (1998) and of Sirangelo & Versace (2002).

## FLaIR APPLICATIONS

This section reports the results that are obtained applying FLaIR model to some Italian landslides triggered by rainfall. A list of the analysed landslides, with synthetic information about their lithological and kinematic characteristics, is reported in Table 1. The definition of the lithological characteristics reproduces the scheme proposed by Amanti *et al.* (1996), while the kinematic characteristics of the movements are identified according to the Varnes classification (1978). In the application of the FLaIR model, the convolution has been attempted between the beta, exponential, double exponential and gamma function and the daily rain recorded in the raingauges near to the unstable areas. Best results were obtained with the gamma function. By this analysis it has been possible to find the admissibility field of the parameters and, once selected a suitable set of them, it has been possible to evaluate the transfer function and the corresponding mobility function with its critical value $Y_{cr}$. To furnish an example of the results, the former computations are depicted in Figs 1 and 2 for the Costigliole landslide, located in the central part of Piedmont region. The dates of the historical movements are November 1951, 10 April 1957, November 1968, September 1973,

**Table 1** Selected landslides.

| Location | Province | Dates of movements | Raingauge | Rainfall time series | Lithology | Kinematic mechanism |
|---|---|---|---|---|---|---|
| Agnona | Vercelli | 15/11/51<br>4/11/68 | Borgosesia | 1951–1986 | uncohesive earth | earth flow |
| Castagnole Monferrato | Asti | 16/02/72 | Castagnole Monferrato | 1953–1986 | flysch | rotational slides |
| Ciglié | Cuneo | Autumn '59<br>19/04/60<br>1/06/61 | Clavesana | 1951–1986 | flysch | translational slides |
| Costigliole d'Asti | Asti | November '51<br>10/04/57<br>November '68<br>September '73<br>4/02/74 | Castagnole Lanze | 1951–1986 | uncohesive earth | rotational slides |
| Masseranga | Vercelli | 10/11/51 | Coggiola | 1951–1986 | uncohesive earth | earth flow |
| Monte-castello | Alessandria | 27/12/60<br>25/04/61 | Sale | 1951–1986 | debris | debris flow |
| Acri | Cosenza | 31/01/81 | Acri | 1922–2000 | weak rock | slides |
| Africo | Reggio Calabria | 6/12/33<br>18/10/51<br>29/12/72 | San Luca | 1925–2000 | thickened earth | translational slides |
| Careri | Reggio Calabria | 18/10/51<br>2/01/73 | Platì | 1920–2000 | thickened earth | rotational slides |
| Petilia Policastro | Catanzaro | 2/12/33<br>29/12/73 | Petilia Policasto | 1921–2000 | thickened earth | – |
| San Pietro in Guarano | Cosenza | 30/01/31<br>26/01/81 | San Pietro in Guarano | 1922–2000 | weak rock | translational slides |
| Verzino | Catanzaro | 8/01/91 | Verzino | 1921–2000 | thickened earth | complex |
| Satriano | Catanzaro | 18/10/51<br>2/01/73 | Chiaravalle Centrale | 1921–2000 | thickened earth | – |
| Senise | Matera | 30/03/73<br>5/03/85 | Senise | 1921–2000 | debris | debris flow |

4 February 1974. The rainfall was recorded in the nearby raingauge of Castagnole Lanze and consists of daily rainfall for the periods 1951–1986. For the set of landslides analysed here it has been possible to observe remarkable analogies, synthetically described in this paragraph, among the cases examined by the model. For every simulated landslide, the expression of the transfer function $\psi(.)$ more suited to reproduce rain–landslide is, as aforementioned, the gamma function. Its adaptability to reproduce the physical phenomena of the examined slopes springs from the various possible combinations of their parameters, $\alpha$ and $\beta$, that confer to the function different shapes. This characteristic allows the gamma function to describe both the landslide typologies triggered by the rains immediately antecedent to the event and the landslide typologies strongly influenced by the rains not immediately antecedent to the event. In all the cases analysed here the estimation of the parameters, $\alpha$ and $\beta$, is substantially unaffected by the values assigned to $h_0$ inside its physical meaningful range.

The more important consideration about the results obtained is that landslides with similar ground typologies have shown similar transfer functions and, then, similar

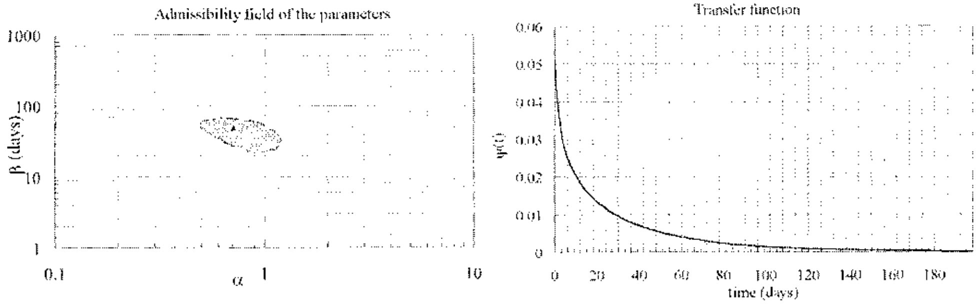

**Fig. 1** Admissibility field of the parameters with chosen set α = 0.7, β = 45 days and relative transfer function.

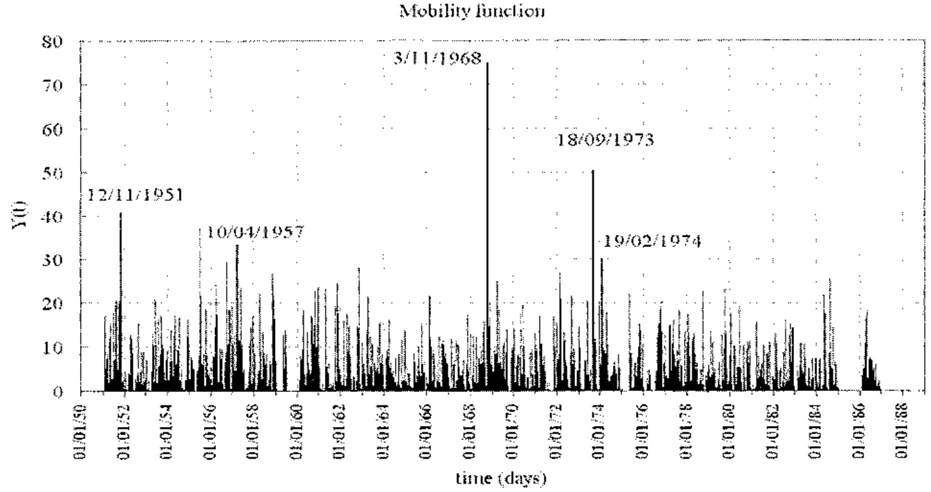

**Fig. 2** Mobility function for the set of parameters α = 0.7, β = 45 days.

hydrological responses. The transfer function results, in fact, similar in the following landslide groups: Africo, Careri, Verzino, Petilia Policastro, Montaldo Scarampi and Satriano (group 1); Agnona, Costigliole d'Asti and Masseranga (group 2); Castagnole Monferrato and Ciglié (group 3); Acri and San Pietro in Guarano (group 4) and Montecastello and Senise (group 5). These landslides have different kinematical characteristics, but they have similar lithology. To illustrate this result, the Fig. 3 report the transfer function ψ(.) for each of five groups of landslides with the same lithology. Finally, Fig. 4 shows a comparison among the averaged transfer functions for each landslides group.

## CONCLUSIONS

This work shows that the FLaIR model describes the relationships of rainfall-landslides by transfer functions whose shapes appear strictly linked to the involved

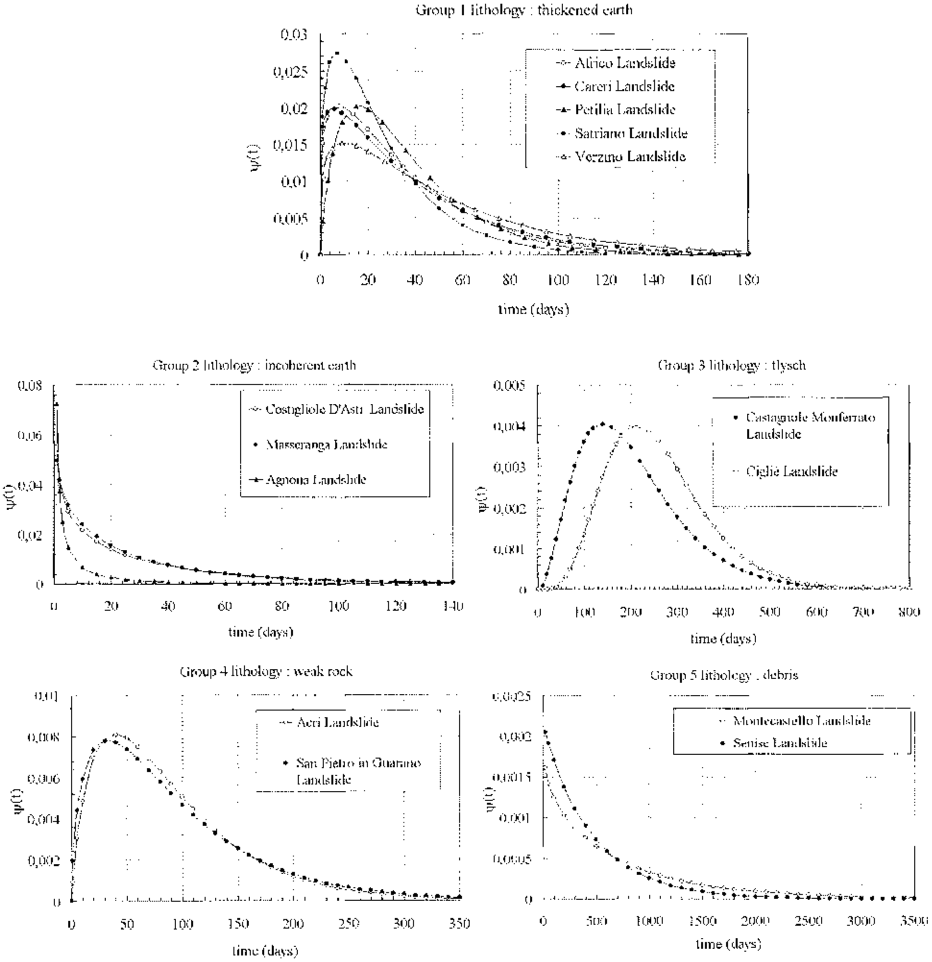

**Fig. 3** Behaviour of transfer functions for the landslide groups.

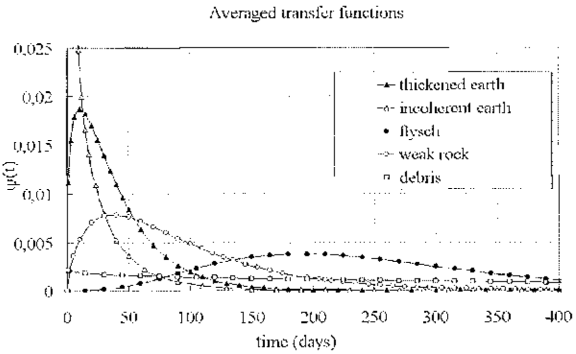

**Fig. 4** Comparison of the averaged transfer functions of the landslides groups.

lithology. This result suggests that further study in this area may lead to the finding of transfer function meaningful parameters able to describe the relationship rainfall-landslides only on the basis of the lithology involved in the phenomenon. The main advantage of this improvement would be the possibility of an application of the FLaIR model to landslides with lack of adequate information about rainfall and historical movements.

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