Predicting rainfall-induced movements of slides in stiff clays

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Facoltà di Ingegneria - Università di Salerno (Italy)
Presentation outline

- Displacements hazard analysis of landslides in clayey soils
- Proposed method
- Calibration, validation, prediction phases
- Numerical results
- Final comments
Active landslides in clayey soil

Varnes (1978)

<table>
<thead>
<tr>
<th>TYPE OF MOVEMENT</th>
<th>TYPE OF MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROCKFALL</td>
</tr>
<tr>
<td>FALLS</td>
<td>Rock fall</td>
</tr>
<tr>
<td>TOPPLES</td>
<td>Rock topple</td>
</tr>
<tr>
<td>SLIDES TRANSLATIONAL</td>
<td>Rock slide</td>
</tr>
<tr>
<td></td>
<td>Rock flow</td>
</tr>
<tr>
<td>FLOWS</td>
<td>(deep open)</td>
</tr>
</tbody>
</table>

COMPLEX - Combination of two or more principal types of movement

Figure 2: Types of landslides. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978).

Cruden & Varnes (1996)

<table>
<thead>
<tr>
<th>Velocity Class</th>
<th>Description</th>
<th>Velocity (mm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Extremely Rapid</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>6</td>
<td>Very Rapid</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>5</td>
<td>Rapid</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>3</td>
<td>Slow</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>2</td>
<td>Very Slow</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Extremly SLOW</td>
<td></td>
<td>$5 \times 10^7$</td>
</tr>
</tbody>
</table>

Activity State

- Active
- Reactivated
- Suspended
- Inactive
- Dormant
- Abandoned
- Stabilised
- Relict

Displacement rate

- first failure
- post-failure
- occasional reactivation
- active landslide

Materials
- Rocks
- Structurally complex formations
- Clay
- Soils and fine sands
- Debris and coarse granular
- Truly collapsible (loess, ...
- Others (residual soils,...)

Event
- Controlling laws and parameters
- Preceding factors
- Triggering or aggravating factors
- Revealing factors
- Consequences
"Rainfall induced slow-moving slides in stiff clays"

**Varnes (1978)**

<table>
<thead>
<tr>
<th>TYPE OF MOVEMENT</th>
<th>TYPE OF MATERIAL</th>
<th>BEDROCK</th>
<th>ENGINEERING SOILS</th>
</tr>
</thead>
</table>
|                  |                  | Rock fall | Predominantly gravelly  
|                  |                  | Debris fall | Predominantly fine  
|                  |                  | Earth fall | Predominantly silty  
| FALLS            |                  | Rock slide | Predominantly gravelly  
|                  |                  | Debris slide | Predominantly fine  
|                  |                  | Earth slide | Predominantly silty  
| TOPPLES          |                  | Rock topple | Predominantly gravelly  
|                  |                  | Debris topple | Predominantly fine  
|                  |                  | Earth topple | Predominantly silty  
| SLIDES           |                  | Rock slide | Predominantly gravelly  
|                  |                  | Debris slide | Predominantly fine  
|                  |                  | Earth slide | Predominantly silty  
| TRANSLATIONAL    |                  | Rock flow | Predominantly gravelly  
|                  |                  | Debris flow | Predominantly fine  
|                  |                  | Earth flow | Predominantly silty  
| LATERAL SPREADS  |                  | Rock spread | Predominantly gravelly  
|                  |                  | Debris spread | Predominantly fine  
|                  |                  | Earth spread | Predominantly silty  
| FLOWS            |                  | Rock flow (deep scoop) | Predominantly gravelly  
|                  |                  | Debris flow (soil scoop) | Predominantly fine  
|                  |                  | Earth flow | Predominantly silty  
| COMPLEX          |                  | Combination of two or more principal types of movement |

Figure 2: Types of landslides. Abbreviated version of Varnes’ classification of slope movements (Varnes, 1978).

**Cruden & Varnes (1996)**

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</tr>
<tr>
<td>2</td>
<td>Very Slow</td>
<td>$5 \times 10^{-8}$</td>
</tr>
<tr>
<td>1</td>
<td>Extremely SLOW</td>
<td>$5 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

**Activity State**

- **Active**
  - Reactivated
  - Suspended
- **Inactive**
  - Dormant
  - Abandoned
  - Stabilised
  - Relict

**Reactivated slides in stiff clay or clay shale:**

- *slope movements localized along a shear zone*
- *residual shear strength* at the sliding surface
- *low rate of displacements* related to the stress level at the sliding surface
- *increase in pore pressures* in the vicinity of shear surfaces

**RAINFALL**

- Governing both the pore pressure regime in the slope and the rate of the displacements
Displacements hazard analysis

Landslide risk management

Fell et al. (2005)

Frequency = measure of the likelihood (i.e. conditional probability) of an outcome, given a set of data, assumptions and information, expressed as the number of occurrences of an event in a given time.

In this case the EVENT is not FAILURE, but the occurrence of movements along the sliding surface (and their prediction with time).
Modeling rainfall induced landslide displacements at site scale

Categories of models

**Black-box models**

**empirical relationships** between soil movements and their causes

(Flageollet et al. 1999; Mandolini and Urciuoli 1999; Mayoraz and Vulliet 2002; Musso and Provenzano 2004; Petley et al. 2002, 2005)

**Physically-based and “mixed” models**

the **mechanical behavior of the soil** is explicitly taken into account

(models can be defined as “mixed” when they employ conceptual schematizations and/or simplifications of the phenomenon within a physically-based framework)

The proposed numerical method

A numerical procedure to compute displacements along a pre-existing slip surface

Fig. 28. From hydrologic conditions to factor of safety and rate of displacement, and related relations

Leroueil (2001)
Calibration of models by inverse analysis

**Initial Input Parameters**

**Numerical Model**

1. Compute Objective function $S(b)$
2. Compute Sensitivity matrix $X$
3. Perform Non-linear Regression

- Perturb parameter $b_k$ (by user-defined amount)
- Calculate $X_{ik} = \delta y_i / \delta b_k$ (for $i = 1$ to $ND$)

**Is the model optimized?** (convergence criteria)

- **YES**
  - $ND = \text{Number of observations}$
  - $NP = \text{Number of parameters to optimize}$
  - $S(b)$ changes less than user-defined amount for 3 sequential iterations

- **NO**
  - Updated Input parameters

**Optimized Input Parameters**

---

**UCODE** (Poeter and Hill, 1998)

\[
S(b) = \left[ y - y'(b) \right]^T \omega \left[ y - y'(b) \right] = e^T \omega e
\]

\[
b_{r+1} = b_r + \rho_r d_r
\]

\[
(C^T X^T \omega X C + Im_r) C^{-1} d_r = C^T X^T \omega (y - y'(b_r))
\]

\[
C_{\omega} = \left[ (X^T \omega X)_{ij} \right]^{1/2}
\]

\[
\left| d^T / b' \right| < TOL
\]
Validation of models

Reliability and Accuracy of numerical predictions

\[ S(b_j) = \text{Objective function} \]

Measure of the error between measured data and computed values (function of the calibrated parameters, \( b_j \))

\[ s^2 = S(b_j) / ND = \text{Error variance} \]

Measure of the “model error” taking into account the number of observations used, ND

\[ \sigma_j = \text{Standard deviation of estimated parameter } b_j \]

\[ \text{CoV}_j = \sigma_j / \mu_j = \text{Coefficient of variation} \]

*If the model correctly represents the system, CoV\(_j\) can be thought of as a measure of the likely accuracy of the estimate.*
The calibration, validation and prediction phases

Case study (Bertini et al. 1984, 1986)

Well instrumented case study
(4.5 years of monitoring data)
### The calibration, validation and prediction phases

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Date</th>
<th>Monitoring data: ( R(t) )</th>
<th>Monitoring data: ( u(t) )</th>
<th>Monitoring data: ( v(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15/02/80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>12/10/80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>07/10/81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_1 = 1050 )</td>
<td>31/12/82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1590</td>
<td>23/06/84</td>
<td></td>
<td></td>
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<tr>
<td>2130</td>
<td>12/85</td>
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**Analysis time = \( T_1 \)**
The calibration, validation and prediction phases

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</table>

$R(t)$

$u(t)$

$F(t)$

$v(t)$

Analysis time = $T_1$

Computed results

Monitoring data: $R(t)$

Monitoring data: $u(t)$

Monitoring data: $v(t)$
The calibration, validation and prediction phases

<table>
<thead>
<tr>
<th>Time (days)</th>
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**Analysis time** = $T1$

- **R(t)**: Monitoring data: $R(t)$
- **u(t)**: Monitoring data: $u(t)$
- **F(t)**: Monitoring data: $v(t)$

Phases:
- Yellow: Calibration
- Red: Validation
- Green: Prediction
The calibration, validation and prediction phases

<table>
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<tr>
<th>Time (days)</th>
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</table>

Monitoring data: R(t)

Monitoring data: u(t)

Monitoring data: v(t)

Phases:
- Calibration
- Validation
- Prediction

Rainfall Scenarios
The calibration, validation and prediction phases

Analysis time = $T_2$

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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- **R(t)**
- **u(t)**
- **F(t)**
- **v(t)**

Monitoring data:
- $R(t)$
- $u(t)$
- $F(t)$
- $v(t)$

Phases:
- Yellow: Calibration
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The calibration, validation and prediction phases

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Analysis time = T2
The calibration, validation and prediction phases

**Time (days)**: 0 240 600 1050 T2 = 1590 2130

**Date**
- 15/02/80
- 12/10/80
- 07/10/81
- 31/12/82
- 23/06/84
- 12/85

**Monitoring data:**
- R(t)
- u(t)
- v(t)

**Phases**
- Calibration
- Validation
- Prediction

**Analysis time = T2**
The calibration, validation and prediction phases

\[ R(t) \]
\[ u(t) \]
\[ F(t) \]
\[ v(t) \]

**Monitoring data:**
- \( R(t) \)
- \( u(t) \)
- \( v(t) \)

**Phases**
- **Calibration**
- **Validation**
- **Prediction**

**Analysis time \( T_2 \)**

<table>
<thead>
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- \( T_2 = 1590 \)
- 15/02/80
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- 12/85

**Time (days):**
- 0
- 240
- 600
- 1050
- \( T_2 = 1590 \)
- 2130
The calibration, validation and prediction phases

Analysis time = T1

Date
0 240 600 1050 23/06/84 12/85
15/02/80 12/10/80 07/10/81 31/12/82

Recorded Rainfall

Total number of analyses = 2

Phases
- Calibration
- Validation
- Prediction
The calibration, validation and prediction phases

<table>
<thead>
<tr>
<th>Time (days)</th>
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Recorded Rainfall

- Rs1
- Rs2
- ...
- RsN

Total number of analyses = 2 x N
The calibration, validation and prediction phases

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Calibration & Validation

Total number of analyses = 2

Analysis time = T2
The calibration, validation and prediction phases

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</table>

**Recorded Rainfall**

**Recalibration** of the models
The calibration, validation and prediction phases

Time (days) | 0 | 240 | 600 | 1050 | \( T_2 = 1590 \) | 2130
---|---|---|---|---|---|---
Date | 15/02/80 | 12/10/80 | 07/10/81 | 31/12/82 | 23/06/84 | 12/85

\[ R(t) \]

\[ u(t) \]

\[ F(t) \]

\[ v(t) \]

**Reformulation** of the models

Analysis time = \( T_2 \)

Recorded Rainfall

Phases
- [ ] Calibration
- \& Validation
- [ ] Prediction
The calibration, validation and prediction phases

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**Recorded Rainfall**

- Rs1
- Rs2
- ...
- RsN

**Total number of analyses = 2 x N**
The numerical results

**Analysis time T1: calibrated and validated analysis**

![Diagram showing head contour lines](image)

- Head contour lines (drawn every 2m) at time \( t = 1040 \) days
- \( g = g(t) \)
- \( q = q(t) \)

- Monitoring data
- Computed results

- Piezometers

**Piezometers**

- \( D8 \)
- \( A2 \)
- \( F10 \)
- \( B5 \)
- \( G12 \)
The numerical results

**Analysis time T1: calibrated and validated analysis**

Analysis time T1: calibrated and validated analysis

- **R(t)**
- **u(t)**
- **F(t)**
- **v(t)**

**Piezometers**

- **A1**
- **B3**
- **B4**
- **C6**
- **C7**
- **G11**
- **G12**

**Head contour lines (drawn every 2m) at time t=1040days**

**Monitoring data**

**Computed results**
The numerical results

**Analysis time T1: calibrated and validated analysis**

- \( u = u(t) \)
- \( f(t) \)
- \( v(t) \)

![Graph showing different slip surfaces and a chart with computed results](image)

The graph includes:
- Slip surfaces
- Incl. B
- Lowermost slip surface

The chart shows computed results with time on the x-axis and force on the y-axis.
The numerical results

**Analysis time T1: calibrated and validated analysis**

![Graphs showing linear and exponential relationships between F(t) and v(t)](image-url)

- **Lowermost slip surface**
- **Linear relationship (LIN)**
- **Exponential relationship (EXP)**

The numerical results...
The numerical results

**Analysis time T1: calibrated and validated analysis**
The numerical results

Analysis time T1: prediction

Rainfall (mm/day)

Analysis time T1: prediction

Recorded
T1-Rs-StMax
T1-Rs-TrMax
T1-Rs-StMin
The numerical results

**Analysis time T1: prediction**

vs

**Analysis time T2: computation**
The numerical results

**Analysis time T2: recalibration**

![Graph showing rainfall and recalibration results](image)
Concluding remarks

The **numerical method** presented herein has been effectively used for the **displacements hazard analysis, at site-scale, of an active slide in stiff clays** characterized by movements along a slip surface induced by rainfall-triggered pore pressure fluctuations.

The comparison between recorded data and numerical results, computed at different “analysis times,” highlights the issue that, **as time passes and more monitoring data are available, a better understanding of the mechanisms behind the activity of the slide is possible** and, when needed, **a recalibration or a reformulation of the numerical models must be carried out**. Performing one or the other depends on the amount and quality of the monitoring data available.
Displacements frequency analysis at site scale

**Scale 1:2.000**

*Central ITALY: Orvieto hill (Lembo Fazio et al. 1984, Tommasi et al. 2005)*
The “scale” issue

Medium and large scale (1:25,000, 1:5,000)

Southern ITALY (Provincia di Benevento)

Total Area = 1.906 km²

(17% affected by landsliding)

Mapped landslides = 13,900
Support slides
### The numerical results

#### Comparison of different analyses

\[ s^2 = \frac{S(b)}{ND} \text{ Error variance (measure of the “model error”) } \]

CoV\(_j\) = \(\frac{\sigma}{\mu}\) = **Coefficient of variation** (measure of the likely accuracy of the estimate)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Time (days)</th>
<th>Seepage model</th>
<th>F-v relationship (LIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ND</td>
<td>S(b)</td>
</tr>
<tr>
<td>T1</td>
<td>0-240</td>
<td>347</td>
<td>570,0</td>
</tr>
<tr>
<td></td>
<td>241-1050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
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</tr>
<tr>
<td></td>
<td>1051-1590</td>
<td>204</td>
<td>545,8</td>
</tr>
<tr>
<td>T2-recalib</td>
<td>0-1590</td>
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Value of input parameter, \(\mu\) (in red when calibrated)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Parameter statistic</th>
<th>Seepage model</th>
<th>F-v relationship (LIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td></td>
<td>H</td>
<td>k1</td>
</tr>
<tr>
<td>T2</td>
<td>Value of input parameter, (\mu)</td>
<td>176 m</td>
<td>1 m/d</td>
</tr>
<tr>
<td>T2-recalib</td>
<td></td>
<td>176 m</td>
<td>1 m/d</td>
</tr>
<tr>
<td>T1</td>
<td>CoV (%) = (\sigma / \mu)</td>
<td>0,2</td>
<td>28,9</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td>0,1</td>
<td>20,9</td>
</tr>
<tr>
<td>T2-recalib</td>
<td></td>
<td>0,1</td>
<td>20,9</td>
</tr>
</tbody>
</table>
Weight of Observations, $w_i$

**Groundwater Model (SEEP transient seepage analysis)**

Observations = 130 – 170 m

$\sigma_i = 1 \text{ m (standard deviation of head values)}, \sigma^2_i = 1 \text{ & } w_i = 1$

If $\sigma_i = 0.2 \text{ m}$ THEN $\sigma^2_i = 0.04 \text{ & } w_i = 25$

i.e. $S(b) = 25 \text{ times the original}$

**Kinematic Model (F vs. v Relationship)**

Observations = 0.0 – 0.3 mm/d

$\sigma_i = 0.1 \text{ mm/d (standard deviation of displacement rates)}, \sigma^2_i = 0.01 \text{ & } w_i = 100$

If $\sigma_i = 0.05 \text{ mm/d}$ THEN $\sigma^2_i = 0.0025 \text{ & } w_i = 400$

i.e. $S(b) = 4 \text{ times the original}$
Recorded
T1-Rs-StMax
T1-Rs-TrMax
T1-Rs-StMin
T2

Time-lag
Time-lag

Head contour lines (drawn every 2m) at time t=1040 days

q=0

hSX

hBX

Piezometers

Computed results
R-u-F-v Procedure : a probabilistic numerical method

(Epistemic) Uncertainty

\[ \delta(t) \]

\[ R(t) \rightarrow \text{Reliability of data} \]

\[ u(t) \rightarrow \text{Aleatory and Statistical uncertainty of input parameters (e.g. CoV)} \]

\[ F(t) \rightarrow \text{Model uncertainty (e.g. error variance)} \]

\[ v(t) \rightarrow \text{Aleatory and Statistical uncertainty of input parameters (e.g. CoV)} \]

\[ \text{Model uncertainty (e.g. error variance)} \]

Uncertainty-based approach for the displacement frequency analysis. By taking into account the different sources of uncertainty of the model, it is possible to quantify the overall uncertainty of the prediction of the displacement rate with time.

The model uncertainty is the a measure of the level of uncertainty about the bias value of the analysis method (Nadim 2002).

Types and sources of uncertainty:

- **ALEATORY uncertainty** (natural randomness of a variable)
- **EPISTEMIC uncertainty** (lack of knowledge of a variable)
  - Measurement uncertainty
  - Statistical uncertainty (due to limited information)
  - Model uncertainty = ratio of the actual quantity to the quantity predicted by a model
Regression analysis

- Objective

Engineering judgment

- Subjective

Setup of analysis → Regression analysis → Optimized results

Start → Engineering judgment → End

Engineering judgment
Parameterization of the inverse analysis

- Soil model
  - Constitutive relationship
- Geotechnical problem
  - Mesh and stress paths
- Numerical implementation
- Field observations
  - Type of observations
  - Soil layers interested
  - Number of observations
- Computational time
- Parameters to optimize

- # parameters
- # uncorrelated parameters
- # relevant parameters
- Total # relevant parameters

Sensitivity analysis

Constitutive relationship

Mesh and stress paths

Soil layers interested

Number of observations

Computational time

Parameters to optimize
References for models (1/2)


References for models (2/2)

Black-box models
(Mandolini & Urciuoli, 1999; Petley, 2005; Voight, 1988?)

Mixed models
(Corominas et alii, 2005; Angeli, 1996; Van Asch, Buma 1997;
Van Asch 2005; Russo, Urciuoli 1999; Ferlisi 2004?; O. Cristescu, Cazacu 2000;
N.D.Cristescu et alii 2002; Hong et alii 2005a; Hong et alii 2005b;
Bonzanigo et alii 2001; Cappa et alii 2004)

Physically based models
(Vulliet, Hutter 1988; Vulliet 1995, Vulliet, Bonnard 1996