Assessment of landslides susceptibility and reactivation likelihood in the Emilia Romagna region (Italy)

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ANTICIPATION

MODEL 1
(2006)

“NEW” LANDSLIDES
(areas outside landslide boundaries)

Triggering areas susceptibility

Multivariate statistic analysis
(logistic regression)

Target Area

Focus

Methods

MODEL 2
(2009)

MAPPED LANDSLIDES

reactivation likelihood

Statistic and Heuristic analysis
(geomorphologic method)

Extent ➔ entire Emilia-Romagna Apennines (11’000 Km²)
**Background: LANDSLIDE INVENTORY MAP - 1:10’000 Scale**

**FEATURES**
- Derived by ‘80-'90 field survey for 1:10’000 geological map;
- Coverage ≈ 11'000 Km²;
- Continuously updated by: aerial photo interpretation, public and private reports, field surveys, InSAR and LiDAR data;
- ≈ 80’000 landslide accumulations (mean Landslide Index ≈ 24%);
- Attended by an historical archive with ≈ 11’000 landsliding events.
- **FEEDBACK:** ≈ 80% of recent events > 5’000 m² and ≈ 95% > 20’000 m² fall totally or partially inside a mapped landslide.

**SHORTCOMINGS**
- It is lacking in small landslides, (especially dormant);
- Maps only landslides accumulations (not depletion areas or main scarp);
- There’s no natively kinematic classification between slides, earth flows and complex landslides…;
- State of Activity (active/dormant) defined in a subjective, inhomogeneous and diachronic way…;
- It’s all but annually updated ➔ active for 20-30 years…
- It DOESN’T PROVIDE ANY INFORMATION ABOUT AREAS OUTSIDE THE LANDSLIDES OR PREDICTIONS ABOUT THE FUTURE EVOLUTION OF THE MAPPED LANDSLIDES.

From SGSS WebGIS: (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico)
Apart of the areas interested by L.267/1998 Hazard Zonization… (~3% Apennine) land-use planning is mainly based on mapped Landslide Activity State

⇒ ACTIVITY STATE is assumed as an HAZARD Indicator!!!

Can we rely (just) on activity state for land-use planning ???

No!
Background: Reference Landslides and LANDSLIDING PROCESS

**SLIDES, EARTH-FLOWS, COMPLEX LANDSLIDES**

different evolution for a (often) common triggering process!

Even huge landslides are often reactivated by small and quite shallow landsliding !!!

(from Bertolini & Pizziolo, 2008)

Spazzavento Landslide
Vergato (BO)
Jan. 2002

↕ 1.5 m

1 - shallow earth-flow

↕ 18 m

2 - partial reactivation

3 – apparently unaffected landslide foot
**Conceptual choices**

- Focused on the forecast of shallow landslide initiation
  - in the areas outside the mapped landslides boundaries.

- Process oriented (landsliding), not on the final product (landslide)
  - calibration on depletion areas (not deposits).

**Strategic choices**

- Base unit: DEM 10x10m (ed. 1976) ➔ high level of detail required (scale 1:5'000 or better).

- Analysis method: Multivariate Binomial Logistic Regression ➔ main advantages:
  1) ideal for dichotomous dependent variable: (landslide YES/NO);
  2) can manage both continuous (slope, etc.) and categorical (litho-technic, etc.) variables;
  3) the results can be directly assumable as landsliding probability.
MODEL 1 ➔ Landsliding Triggering Susceptibility

Modellization process

1. Choice of stable and unstable areas - depletion areas are not mapped in LIM ➔ Local TOP

Unstable Areas ➔ ≈ 112,000 apex cells

Stable Areas ➔ 130,000 “presumably stable” points randomly sampled “far outside” (>30m) mapped landslides (and slope deposits)
3. Preliminary analysis of the independent variables:

1) cross correlation matrix;
2) bivariate (bayesian) analysis
   (for single variables effectiveness).
MODEL 1 ➔ Landsliding Triggering Susceptibility

4. Application of the multivariate regression:

- Calibration (80%)
- Validation (20%)

**Goodness of Fit:**
- -2 Log Likelihood

**Output Coefficients**

**Application to the validation subset**

**Goodness of forecast:**
- ROC Area

**ROC area**

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<thead>
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<th>Model</th>
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<td>1</td>
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<td>2</td>
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<td>3</td>
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<td>4</td>
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<td>5</td>
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<tr>
<td>6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Complexity</th>
<th>ROC area</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.573</td>
</tr>
<tr>
<td>2</td>
<td>0.696</td>
</tr>
<tr>
<td>3</td>
<td>0.708</td>
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<tr>
<td>4</td>
<td>0.748</td>
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<tr>
<td>5</td>
<td>0.769</td>
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<tr>
<td>6</td>
<td>0.780</td>
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7 Continuous DEM derivative + 2 Categorical:
(Lithotechnical Map and Land Use 1976 classes)
Advantages in calibrating the model on the ACTIVE LANDSLIDE only:

1. **Better landslide mapping accuracy**
   (especially in the upper portion of the accumulation);

2. We can be more confident that the **independent variables are representative of the pre-failure conditions** (land-use ’76 is more likely independent from recent/active landslides than from old/dormant ones);

3. Other…
MODEL 1 ➔ Landsliding **Triggering Susceptibility**

5. Results:

Cells calculated: 113,840,217

Mean Susceptibility: 38.2%
MODEL 1 ➔ Landsliding Triggering Susceptibility
MODEL 1 ➔ Landslide Triggering Susceptibility

http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico
What about the mapped landslides?

The evaluation of the reactivation likelihood of the “existing landslides” is a crucial issue for Emilia Romagna region because they are the great most of the areas yearly affected by landsliding events.

HAZARD ASSESSMENT:

<table>
<thead>
<tr>
<th>Reactivations:</th>
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<tbody>
<tr>
<td>1. Total</td>
</tr>
<tr>
<td>2. Partial 1</td>
</tr>
<tr>
<td>3. ...</td>
</tr>
<tr>
<td>4. Partial n</td>
</tr>
</tbody>
</table>

80'000 landslides

- Magnitude
- Return Period

(Climate, Land-Use changes)

We changed questions and wandered:

1) For Land-Use Planning are there actual differences between active and dormant landslides? If yes, can they be quantified?

2) Dormant landslides are all similar with each other or there are some of them “really dormant” and other more “active like”??
PURPOSE: Assess the “reactivation likelihood” of the mapped landslides (with a particular attention to the dormant landslides).

IDEA: Identify and Quantify the “boundary conditions” that promote the landslide reactivation (expert knowledge method).

CONCEPTUAL FRAMEWORK

Reactivation predisposal factors:

1. Landsliding susceptibility in the landslide’s upslope surrounding areas;
2. Influence of the geometrical relationship “active/dormant” landslides;
3. Presence of past events in the historical landslide database.

METHOD ➔ Geomorphologic and Heuristic analysis
1. Landsliding susceptibility in the landslides upslope surrounding areas!

Assumption: the higher is the susceptibility value in the upslope surrounding a mapped landslide, the higher will be the reactivation likelihood of that landslide.

- we calculated the mean susceptibility in the landslide upper surrounding for a distance ≤ 50 m along the flow lines.
Dormant Landslides with "reactivation likelihood" > 80%
MODEL 2 → Mapped Landslides Reactivation Likelihood

60% < $P_R < 80%$

20% < $P_R < 40%$

$P_R < 20%$
...but there’s a problem:
37% of dormant landslides are “touched” by (at least) one active landslide !!!

- They have a reduced or no basin (for the susceptibility calculation);
- If an active landslide “load and push” a dormant one, may reactivate it...
2. Influence of active landslides on the dormant accumulations!

- Codify the “geomorphologist intuition” or “expert knowledge”

Example: what a geomorphologist would say about these three dormant landslides?
We analyzed the geometric relationship between landslides to (empirically) quantify the relative influence of Active vs Dormant landslides!

ADVANTAGES

1. To reduce subjectivity through an homogeneous judgment criteria for the whole region;
2. To automate the relative influence evaluation all over the RER Landslide Inventory Map.

<table>
<thead>
<tr>
<th>N°</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean Aspect difference</td>
</tr>
<tr>
<td>2</td>
<td>Centroids height difference (Q_{FR1} - Q_{FR2})</td>
</tr>
<tr>
<td>3</td>
<td>Areas ratio (A_{FR1}/A_{FR2})</td>
</tr>
<tr>
<td>4</td>
<td>Mean slopes ratio (SLP_{FR1}/SLP_{FR2})</td>
</tr>
<tr>
<td>5</td>
<td>Contact boundary mean curvature</td>
</tr>
<tr>
<td>6</td>
<td>Length of contact zone vs dormant landslide perimeter ratio</td>
</tr>
<tr>
<td>7</td>
<td>Relative position of the contact zone respect the dormant landslide perimeter</td>
</tr>
<tr>
<td>8</td>
<td>Number of active landslides in contact with the dormant</td>
</tr>
<tr>
<td>9</td>
<td>Type of landslide movement in contact with each other</td>
</tr>
</tbody>
</table>
MODEL 2 ➔ Mapped Landslides Reactivation Likelihood  2/3

➔ Additive and Multiplicative scores Synthesis ➔ INFLUENCE INDEX: A ➔ D

Let’s see the QUIZ results…
3. Historical Reactivation records: The Historical Landslide Events Database!

So far it counts ~11’000 events with this data:

- event date (variable precision);
- location;
- main descriptive features;
- triggering causes;
- damages;
- historical documentation (eventual).

Model statement: If a certain landslide has been activated in a known past, it will likely reactivate again!!!
Waiting for future model development, so far the combination of the three sub-models:

1) Upslope Susceptibility
2) Geometric “Influence Index”
3) Known past reactivation

is performed in an easy way:

Dormant accumulations that have “at least one” of these conditions:

1. Upslope mean susceptibility higher than a threshold (mean = 48%)
2. Are touched by at least one active landslide with an Influence Index higher than a threshold (I.I. = 20);
3. Have at least one historical reactivation record...

Will be classified as DA = Dormant with High Reactivation Likelihood
MODEL 2 ➔ Mapped Landslides Reactivation Likelihood
Example 1: - Fravica Landslide - Pianello Val Tidone (PC) - Last reactivation: January-April 2009

Pre-Event Inventory Map

Model components:
1. Mean Upslope Susceptibility = 56%
2. No active landslides in contact
3. N°2 previous known partial reactivation (1964-1965)

High Reactivation Likelihood!
Example 2: Poggio Baldi Landslide - Corniolo - Santa Sofia (FC) - Last reactivation: 19 March 2010

Pre-Event Inventory Map

Model components:
1. Mean Upslope Susceptibility = 24%
2. 1 active landslides $\Rightarrow$ I.I. = 21.4-24.2
3. N°1 previous partial reactivation (1914)

$\Rightarrow$ High Reactivation Likelihood!
Future development:

1. Improvement of the upslope susceptibility assessment (to account also for high susceptibility values inside the landslide perimeter);

2. Use of the historical landslide database to calibrate, by statistical regression, the actually empirical coefficients for the Influence Index.

3. If you have other suggestions we’ll be glad to collaborate...

→ the mandatory requirement for the good models performance is a complete, update and high quality Landslide Inventory Map.