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A spatiotemporal object-oriented data model for landslides (LOOM)

Abstract LOOM (landslide object-oriented model) is here presented as a data structure for landslide inventories based on the object-oriented paradigm. It aims at the effective storage, in a single dataset, of the complex spatial and temporal relations between landslides recorded and mapped in an area and at their manipulation. Spatial relations are handled through a hierarchical classification based on topological rules and two levels of aggregation are defined: (i) *landslide complexes*, grouping spatially connected landslides of the same type, and (ii) *landslide systems*, merging landslides of any type sharing a spatial connection. For the aggregation procedure, a minimal *functional interaction* between landslide objects has been defined as a spatial overlap between objects. Temporal characterization of landslides is achieved by assigning to each object an exact date or a time range for its occurrence, integrating both the time frame and the event-based approaches. The sum of spatial integrity and temporal characterization ensures the storage of vertical relations between landslides, so that the superimposition of events can be easily retrieved querying the temporal dataset. The here proposed methodology for landslides inventorying has been tested on selected case studies in the Cilento UNESCO Global Geopark (Italy). We demonstrate that the proposed LOOM model avoids data fragmentation or redundancy and topological inconsistency between the digital data and the real-world features. This application revealed to be powerful for the reconstruction of the gravity-induced deformation history of hillslopes, thus for the prediction of their evolution.

Keywords Object-oriented · Landslide system · Landslide complex · Landslide object

Introduction

In the field of natural hazards, landslides are one of the most widespread and frequent phenomena, related both to natural and anthropogenetic causes and triggers, sometimes with catastrophic outcomes such as casualties (Cascini et al. 2008; Petley 2012; Barla and Paronuzzi 2013). Landslides often also interfere with human activities, impacting on urban areas, infrastructures such as roads, tunnels, bridges, pipelines and areas related to other socioeconomic activities causing significant economic losses (Crosta et al. 2004; Evans and Bent 2004; Pankow et al. 2014; Bozzano et al. 2017; Marinos et al. 2019). In this framework, sometimes structures or infrastructures are faced with complex arrangements of landslides rather than a single movement (Barredo et al. 2000; Schädler et al. 2015; Uzielli et al. 2015; Bozzano et al. 2016). Such complexity can be related to different spatiotemporal arrangements of landslides: there can be a frequent occurrence of phenomena in a relatively small area (Corbi et al. 1996; Crozier 2010; Berti et al. 2013), or the spatial overlap of successive landslide occurrences, like converging flow-like movements (Cascini et al. 2008; Schädler et al. 2015), or relatively shallower phenomena developed over deep-seated movements (Guida et al. 1987; Guerricchio et al. 2000; Murillo-García et al. 2015), or partial mobilizations of previous landslides in nested structures (Lee et al. 2001), or various superimpositions of different landslide types (Stefanini 2004; Guida et al. 2006; Valiante et al. 2016). Overlapping landslides derive from the temporal sequence of events and some authors also suggested the concept of *path dependency* for landslide susceptibility analysis, stating that preexisting landslides could be a predisposing factor for future phenomena (Samia et al. 2017a, b). Besides spatial arrangements of landslides, even dealing with a single landslide implies to face its inner complexity, i.e. describe its components (Parise 2003; Dufresne et al. 2016; Morelli et al. 2018; Wang et al. 2018).

Existing inventories currently are not structured to store and retrieve such complexity of landslide arrangements, since landslides are most frequently represented just as point locations or as a coverage of adjacent non-overlapping polygons (Van Den Eeckhaut and Hervás 2012; Van Den Eeckhaut et al. 2013; Herrera et al. 2018). This flaws could be addressed both to the lack of a model describing the spatiotemporal overlap of phenomena, and to the fact that managing overlapping features within a single dataset is quite challenging using common file formats such as ESRI shapefiles or geodatabases. Despite this limitation, representing geospatial features as adjacent tiles can be useful for various applications, such as coverages, administrative boundaries, or cadastral management, but, when dealing with landslide sets, it becomes a consistency problem. Representing nested or overlapping landslides as coverage of adjacent tiles produces a logical inconsistency between the topology of the data and the topology of the real-world features, since vertical relations between landslide events such as *under-over*, *contained-contains*, *overlapping-overlapped*, are not preserved causing a loss of useful information. In addition, current approaches in multi-temporal landslide inventories are usually based on the snapshot or "time-slices" model (Dragicévić 2004; Guzzetti 2006; Samia et al. 2017a), storing the landslide inventory at a specific time or landslide events that occurred in a specific time frame within different datasets. Having multiple datasets for representing multi-temporal information results in data fragmentation and poor management of temporal relations.

Current approaches in temporal characterization of landslide inventories can be traced back to three main strategies: (i) static inventory, as a single snapshot representing all the recognized landslides at a specific time point in a single dataset (Guerricchio et al. 2000; Carrara et al. 2003; Van Westen et al. 2003; Conoscenti et al. 2008; Yalcin 2008; Brunetti et al. 2014; Schlögel et al. 2018; Marinos et al. 2019); (ii) multi-temporal snapshot-based inventory, as a collection of at least two snapshots contained in different datasets, where each snapshot has its own time reference (Corbi et al. 1999; Guida et al. 2006; Coico et al. 2013; Lupiano et al. 2019); (iii) multi-temporal inventory time frame- or event-based, as different datasets containing landslides occurred in a specific time frame (from dd/mm/yyyy to dd/mm/yyyy) or triggered by a specific event (in such a case, usually the exact date of occurrence is known). In some cases, time frames characterization is qualitative, based on geomorphological properties of landslides (relict, very old, old, recent) (Cascini et al. 2008; Murillo-García et al. 2015; Martino et al. 2017; Samia et al. 2017a; Roback et al. 2018; Lupiano et al. 2019).

To describe spatial and temporal arrangements of landslide sets, Guida et al. (1988) introduced the concept of *landslides system* as "*a set of complex landslides* (sensu Varnes 1978; Cruden and Varnes 1996) *ascribable to a common initial slope deformation which, acting on long-term evolution, develops into differentiated gravity-driven morpho-types referring to slope movements, different in type of, age and state of activity*". Successively, the authors extended the description of landslides associations (set) based on movement types and state of activity (Guida et al. 1995). Since then, such classification scheme and terminology has been used for the description of complex arrangement of landslide set on wide areas in southern Italy, specifically in emergency management and landslide hazard assessment (Guida et al. 2006; Coico 2010; Left Sele River Basin Authority 2012; Coico et al. 2013; Valiante et al. 2016).

Starting from the overall topic of the definition of the relations between complex arrangements of landslides involving engineering works, this paper aims to (i) define a model, based on the concept of "landslide system", for the description of associations of landslides and their spatial and temporal relations; (ii) implement such a model in a database structure capable of storing both spatial and temporal information in a single dataset, thus avoiding physical fragmentation and logic inconsistency of the data and allowing to quickly retrieve information about the number of interacting phenomena, their temporal occurrence (i.e. the slope evolution), their spatial relations and so on; and (iii) assess its performance in selected case studies.

The model has been developed on the basis of an original object-oriented and hierarchical classification for landslides defined in Valiante et al. (2020), starting from the proposal in Campobasso et al. (2018) for the Italian Guide Line for Geomorphological Mapping. In this hierarchy, landslides define the focal level and two levels of aggregation based on topological relations describing various association of landslides are built. After, just one level of decomposition containing landslide components has been defined, leaving a second one (landslide elements) for further geospatial, topological and mereological researches.

The object-oriented data model has been chosen as optimal because of its intrinsic hierarchical structure and its flexibility in the classification procedures. In addition, it is adaptable to any natural system and capable to define procedures (called methods or functions) to dynamically access and manipulate classes attributes, reducing the volume of information needed to be actually stored (Egenhofer and Frank 1987; Worboys et al. 1990; Worboys 1994; Kösters et al. 1996). This model describes, structures and manage the landslide associations or set, taking into account both their spatial and temporal relations, Finally, it is a tool to build up, update and manage landslide inventories using any of the existing classifications for movement types (Varnes 1978; Cruden and Varnes 1996; Hungr et al. 2014). As it regards the mapping techniques not dealt within this paper, we refer to the existing literature (Guzzetti et al. 2012; Auflič 2017; Hung et al. 2017; Martino et al. 2017; Lupiano et al. 2019).

As a demonstration of its reliability and suitability, in the following, after a short theoretical background, the proposed method is more extensively illustrated and then its application to two selected case studies in the Cilento UNESCO Global Geopark (Italy) is shown. The first case refers to a deep-seated, slow-moving and reactivated landslide involving structurally complex formations, while the second one refers to fast-moving, repeated landslides on steep, rocky slopes.

Theoretical background

Object-oriented data modelling

Object orientation concepts were developed in the 1960s as structures for programming languages. According to Lewis and Loftus (2015) and Phillips (2018), the key concepts or primary features of any object-oriented language are as follows:

- Abstraction: features can be described through a classification, i.e. any feature is modelled with a class definition containing both its description and variables (attributes) and the procedures or functions available for that class (methods). Any instance (practical example) of that specific class is called object. Relations between classes are modelled through generalization, association and aggregation.
- Encapsulation: variables and functions definition inside a class allow final users to manipulate objects through methods without interfering with the original properties of the class itself (data hiding).
- Inheritance: classes can contain subclasses which share their superclass attributes and methods.
- Polymorphism: different object types have their own different implementation of the same function or method.

Egenhofer and Frank (1987) firstly proposed an object-oriented model for the manipulation of spatial information based on the abstraction concepts of classification, generalization and aggregation, introducing a hierarchical structure with single or multiple inheritance of attributes and methods. Following their pioneering work, a series of concepts and structures have been proposed. Abstraction mechanisms to describe a system assume that any entity can be represented by exactly one object regardless of its complexity or inner structure using classification (Dittrich 1986). Complexity is modelled through generalization, association and aggregation (Egenhofer and Frank 1992). Generalization groups several classes of objects with common operations into a more general superclass, and it is described by the relations *is-a* or *can-be-a*, the inverse process is specialization; association relates two or more independent objects which can have an identity as a group, the relations *member-of* or *a-set-of* describe it; aggregation relates an entity with its components and is described by the relations *part-of* or *consists-of*, the inverse process is decomposition. To better model interactions among the defined classes, Worboys et al. (1990) introduced *functional relationships* between objects as links describing their mutual connections. Upon these bases, several data structures have been proposed both for general purpose spatial databases (Egenhofer and Frank 1992; Kösters et al. 1996; Fonseca and Egenhofer 1999; Borges et al. 2001; Khaddaj et al. 2005) and specialized data, such as census/administrative units (Worboys et al. 1990), topographic information (Shahrabi and Kainz 1993), archaeology (Tschan 1999) and city planning (Gröger et al. 2004). Moreover, different specialized softwares have been developed based on object-oriented models (Câmara et al. 1996; Kösters et al. 1997; Posada and Sol 2000; Chen et al. 2012). Talking about landslides, applications of object-oriented procedures usually refer to the automatic recognition, extraction and mapping of landslide features from grid-based datasets using object-based image analysis techniques (OBIA) (Dramis et al. 2011; Blaschke et al. 2014; Hölbling et al. 2015 among the others).

Object-oriented methods strongly rely on relationships among classes. These relations can be such as generalization-specialization, aggregation-decomposition, or association: all these connections define a hierarchical structure. In a hierarchical structure, classes and subclasses are related by parent-child relationship, while classes sharing a common superclass are called siblings (Tsichritzis and Lochovsky 1976; Singh et al. 1997; Glover et al. 2002; Malinowski and Zimányi 2004). A hierarchy is defined as a multi-layered system, where each level can be decomposed until a non-decomposable level is defined (Simon 1962; Odum and Barrett 2005; Wu 2013). While the object-oriented classification defines specific relationships among classes, hierarchical levels are a relative structure as they depend on the purpose to which they are applied. Based on the objective of any analysis, the centre of the hierarchy (Focal level) can be any object of interest, and its parents define levels of generalization or aggregation (levels + x_n), while its children define levels of specialization or decomposition (levels − x_n) (Wu 1999, 2013).

Spatiotemporal data modelling

Typical queries and operations on geographical objects often are based on their spatial properties and temporal attributes. Spatial relationships can be classified into three main categories (Egenhofer and Herring 1990a):

- Geometric relationships: anything that can be measured within a referenced system, such as distances, directions and angles, areas, volumes, etc.
- Spatial order relationships: regarding the objects ordering in a referenced space. These properties are usually dualistic, and typical examples are *in front–behind* or *above–beneath*.
- Topological relationships: describing the relative arrangements of objects in space. These properties are usually invariant under common transformations or distortions such as translation, scaling, rotating, stretching, etc.

Temporal queries require the modelling and storage of temporal information. Time could be expressed as a point or as an interval where time points represent exact moments, and time intervals represent any time span. However, both these two definitions can be generalized in time intervals, as time points are a relative concept and depend on the time scale in which they are referred (Allen 1983; Nebel and Bürckert 1995; Van Beek and Manchak 1996). Relations among time intervals are defined in Allen (1983), describing their relative position in the time dimension. Temporal Geographic Information Systems (T-GIS) are defined as GIS capable of storing and manipulating temporal information in order to perform spatiotemporal queries (Yuan 2008).

Time can be handled in different ways in GIS, thus in databases. Two recurrent models are the *snapshot model* and the *event-based model*. In a snapshot model, each dataset represents the state of a system in a precise time frame; it could be considered as a photography of a system's state in a specific instant (Peuquet and Duan 1995; Dragicévić 2004; Gutierrez et al. 2007). In event-based approaches, objects within a dataset are characterized with temporal attributes describing their time persistence (Peuquet and Duan 1995; Worboys and Hornsby 2004). Referring to landslides, an event can be described as a set of landslides mobilized by the same trigger (Napolitano et al. 2018) or by *domino effect* (Martino 2017). The main difference between these two models is that in the snapshot model the temporal characterization is assigned to the whole dataset, while in the event-based approach, objects within the dataset have their own temporal characterization. Using an event-based approach reduces data fragmentation, allowing storage of all the information within one dataset and, at the same time, reduce data redundancy, which reflects a reduction in data volume.

LOOM reference models and data structure

Topological models

To describe spatial relations between objects, two topological models for spatial reasoning have been exploited in this work: the dimensionally extended nine-intersection model (DE-9IM) (Egenhofer and Herring 1990a, b; Egenhofer and Franzosa 1991; Clementini et al. 1994) and the region connection calculus (RCC) (Randell et al. 1992; Cohn et al. 1997). The DE-9IM is a topological model used to describe the spatial relations of two geometries (points, lines, polygons) in two dimensions. The basic assumption for this model is that each object in the R^2 space has an interior ($I(a) = a^o$), a boundary ($B(a) = \partial a$) and an exterior ($E(a) = a^e$) and the spatial relation of two geometries is evaluated in the form of a 3x3 intersection matrix (Equation 1).

$$DE9IM(a,b) = \begin{bmatrix} \dim(a^o \cap b^o) & \dim(a^o \cap \partial b) & \dim(a^o \cap b^e) \\ \dim(\partial a \cap b^o) & \dim(\partial a \cap \partial b) & \dim(\partial a \cap b^e) \\ \dim(a^e \cap b^o) & \dim(a^e \cap \partial b) & \dim(a^e \cap b^e) \end{bmatrix} \quad (1)$$

In this equation *dim* is the maximum number of dimensions of the intersection of the interior, boundary and exterior of geometries *a* and *b* (dim(point) = 0, dim(line) = 1, dim(polygon) = 2). These values can be expressed as Boolean values where FALSE means non-intersection and TRUE any other value. The resulting matrix can be also expressed as a 9 characters alphanumeric string. RCC describes regions by their possible relations to each other. RCC8 consists of 8 basic relations that are possible between two regions. Integrating the two models, RCC8 relation can be converted in 12 DE-9IM matrices and thus in 12 alphanumeric strings which can be implemented in a database dictionary.

Landslide inventory and landslide maps

The basic landslides inventory has been built by means of field survey, remote sensing data analysis, such as aerial photographs and collecting data from previous existing inventories. Following the procedure proposed by Dramis et al. 2011 for general geomorphological mapping, inventoried features have been first stored with a symbol-based approach (SGN 1994; APAT 2007; Gustavsson et al. 2008; Gustavsson and Kolstrup 2009; Campobasso et al. 2018). Then, data have been processed in a GIS environment, converting symbols in proper landslide objects, producing a full coverage landslide map (Dramis et al. 2011; Guida et al. 2015). In this full-coverage representation, the overlapping portions between landslides are preserved and not cut as usual, as they are crucial for the aggregation procedures. After these operations, data have been imported in the database designed following the proposed object-oriented model.

In this framework, landslide inventory refers to the digital dataset organized following the model described in the next sections, while a landslide map is a particular representation of the dataset, such as a snapshot of the inventory, landslides occurred in a time frame or during a specific event.

The object-oriented model for landslides

Following the hierarchical and multi-scale model for geomorphological mapping described in Dramis et al. 2011, the focal level (level 0) of the hierarchy is composed by the landslides themselves while two levels of aggregation describe sets of landslides: (i) *landslide complexes* result from the aggregation of landslide with the same type of movement spatially connected (level + 1) and (ii) *landslide systems* are defined as a set of landslides of any type spatially connected (level + 2). A level of decomposition stores *landslide components* (level − 1). In this work, the defined hierarchical and multi-scale classification has been structured in an object-oriented model suitable for database design and rules for the aggregation of landslides based on topological relations have been defined. Time frame and event-based approaches have been integrated in order to store and manipulate the temporal characterization of landslides.

Landslide class (focal level)

This class describes individual landslides, each record identifies a *landslide object*. Referring to the object-oriented classification procedure, the basic *landslide class* is specialized into 21 *landslide subclasses*, meaning that the original 32 types (49, if movements involving different types of soils and rock-ice are distinguished) proposed by Hungr et al. 2014 are grouped into 21 *supertypes*, defined primarily considering the main type of movement, then the involved material. This merging operation has the only purpose to simplify the aggregation procedure for the definition of *landslide complexes* and does not intend to generalize the original classification, in fact, each class here is defined having two movement type attributes, in which types are picked from the original 49 types discussed in Hungr et al. 2014. The 21 *landslide subclasses* that have been defined are listed in Table 1. Any object defined within any of these 21 classes is also a member of their parent class, i.e. the *landslide class*: for example, as the *rock fall class* is a specialization of the *landslide class*, any *rock fall object* is also a *landslide object*.

Landslide complex class (level + 1)

The definition of the *landslide complex class* relies on the concept of functional interaction between objects (Worboys et al. 1990). To form a *landslide complex object*, referring to the DE-9IM topological model, a functional interaction is defined as a two-dimensional topological relation between objects members of the same *landslide subclass*. Based on the RCC8 model, two or more *landslide objects* are eligible for the aggregation in a *landslide complex object* if, and only if their topological relation is *partially overlapping*, *tangential proper part*, *inverse tangential proper part*, *non-tangential proper part* or *inverse non-tangential proper part* and they are member of the same *landslide subclass*. The *equals* relation, even satisfying the functional interaction requirements is unrealistic (Fig. 1a). *Landslide objects* that do not share functional interaction with other *landslide objects*, are reported as "isolated landslides" and do not reach the aggregation phase. Having 21 *landslide subclasses*, the same amount of *landslide complex subclasses* is derived (Table 1). As for the previous classes, any object member of any *landslide complex subclass* is also a *landslide complex object* (Fig. 1b).

Landslide system class (level + 2)

The *landslide system* class is built upon the aggregation of the previously declared classes. To aggregate a *landslide system object*, the condition of functional interaction is defined as a two-dimensional topological relation between two or more *landslide complex objects* or *landslide objects* of any type. In this case, landslides that do not form a complex can be aggregated in a system directly if they have a functional interaction with complexes or other landslides of different type. The topological relations that satisfy the functional interaction condition are the same as for the *landslide complex subclasses*. *Landslide complex objects* that do not share a functional interaction with other objects, as for *landslide objects*, are reported as "isolated landslide complex" (Fig. 1b).

Landslide component class (level − 1)

Landslide components are defined in this class. At this level, major areal features are considered, such as detachment areas, bodies, debris etc. Minor areal features or linear and point features could be considered for a further level of detail (level − 2), but are not included in this work. For now, the implementation has been limited at the actual classes needed for this work. Referring, for example, to the soil rotational slide class (SRS), the subclasses defined are

- SRS detachment area class—containing detachment areas.
- SRS body class—containing rock rotational slide accumulation areas.

Temporal characterization and vertical relations

Each *landslide object* has attached temporal attributes for the time of occurrence which define an event or a time frame. The relationship between landslides and events, or time frames, is many-to-one, meaning that one landslide object corresponds to a single event-time frame, while one event-time frame can contain multiple landslide objects. Time of occurrence can be expressed as an exact value, when the date of occurrence is known, or as a range, when the exact time of occurrence is unknown, but the time frame can be deduced. For landslides contained in the same time interval a relative chronology can be implemented, based on field

Table 1 Landslide object-oriented classification

LOOM Level +2	Level +1 - Landslide complex subclasses	Level 0 - Landslide subclasses	Landslide types (Hungr et al. 2014)
Landslide system class	Rock fall complex class	Rock fall class	Rock fall
			Ice fall
	Soil fall complex class	Soil fall class	Boulder fall
			Debris fall
			Silt fall
	Rock topple complex class	Rock topple class	Rock block topple
			Rock flexural topple
	Soil topple complex class	Soil topple class	Gravel block topple
			Sand block topple
			Silt block topple
	Rock rotational slide complex class	Rock rotational slide class	Rock rotational slide
	Rock planar slide complex class	Rock planar slide class	Rock planar slide
	Rock wedge slide complex class	Rock wedge slide class	Rock wedge slide
	Rock compound slide complex class	Rock compound slide class	Rock compound slide
	Rock irregular slide complex class	Rock irregular slide class	Rock irregular slide
	Soil rotational slide complex class	Soil rotational slide class	Clay rotational slide
			Silt rotational slide
	Soil planar slide complex class	Soil planar slide class	Clay planar slide
			Silt planar slide
			Gravel slide
			Sand slide
			Debris slide
	Soil compound slide complex class	Soil compound slide class	Clay compound slide
			Silt compound slide
	Rock slope spread complex class	Rock slope spread class	Rock slope spread
	Granular soil spread complex class	Granular soil spread class	Sand liquefaction spread
			Silt liquefaction spread
	Cohesive soil spread complex class	Cohesive soil spread class	Sensitive clay spread
	Rock avalanche complex class	Rock avalanche class	Rock avalanche
			Ice avalanche
	Soil dry flow complex class	Soil dry flow class	Gravel dry flow
			Sand dry flow
			Silt dry flow
			Debris dry flow
	Granular soil wet flow complex class	Granular soil wet flow class	Sand flowslide
			Silt flowslide
			Debris flowslide
			Debris flow
			Debris flood
			Debris avalanche

Table 1 (continued)

LOOM Level +2	Level +1 - Landslide complex subclasses	Level 0 - Landslide subclasses	Landslide types (Hungr et al. 2014)
	Cohesive soil wet flow complex class	Cohesive soil wet flow class	Sensitive clay flowslide
			Mud flow
			Earthflow
			Peat flow
	Deep-seated slope deformation complex class	Deep-seated slope deformation class	Mountain slope deformation
			Rock slope deformation
	Shallow slope deformation complex class	Shallow slope deformation class	Soil slope deformation
			Soil creep
			Solifluction

observations, remote sensing data analysis or any other mean. Instead, within the frame of a single event, if multiple landslide objects overlap, an internal "overlap index" is introduced, as an integer number such that if landslide object A lies upon landslide object B, then overlap index of A is higher than overlap index of B. Temporal characterization of landslides is crucial for the management of vertical relationships. In this framework, vertical relationship means both spatial sorting of the type *under–over* and temporal sorting of the type *older–younger*. As for the law of superimposition, older objects lie under younger objects while

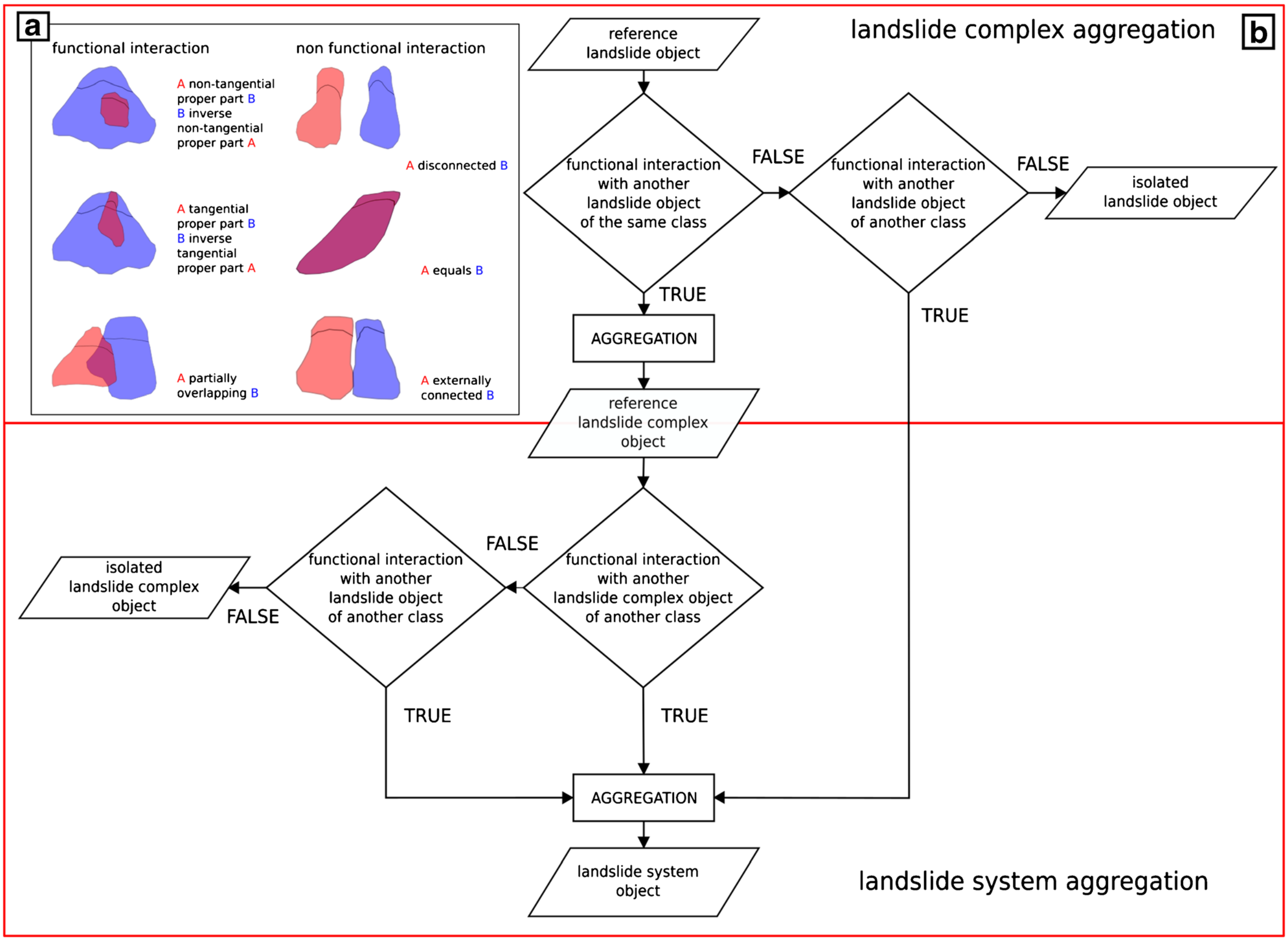


Fig. 1 **a** Topological relationships for the definition of the functional interaction (from Valiante et al. 2020). **b** Logical model for the aggregation of landslide complex objects and landslide systems objects

younger objects lie over older objects. In particular cases where an older object is entirely mobilized by a deeper, younger object (*tangential proper part* or *non-tangential proper part* topological relations), the older object, even being physically over the younger object, loose its “status” of *landslide object* and became part of the new *landslide object* debris. Within the temporal dataset it will be displayed under the younger object, being older. In the case of several overlapping phenomena within the same event, the “overlap index” mentioned before act as secondary sorting parameter.

For better space-temporal data handling, basic topological relations have been integrated with temporal relationships. Based on the 8 relationships of the RCC model and Allen’s paradigms, referring to the object “A” and the object “B”, their topological relationship may vary whether A is younger than B or vice versa:

A Partially Overlap B
A before B→(A overlapped by B∧B overlaps A)
A after B→(A overlaps B∧B overlapped by A)

A Tangential Proper Part B∨A NonTangential Proper Part B
A before B→(A covered by B∧B covers A)
A after B→(A superimposed on B∧B contains A)

A inverse Tangential Proper Part B∨A inverse NonTangential Proper Part B
A before B→(A contains B∧B superimposed on A)
A after B→(A covers B∧B covered by A)

The *Equals* relationship, as mentioned before, is not considered, while the *Disconnected* and the *Externally Connected* relationships are not affected by the temporal statement as their vertical sorting is invariant.

Database design

The database used for this work is *PostgreSQL© 11.0* with *PostGIS© 2.5* extension. Database maintenance and manipulation is achieved using PgAdmin4 and the *pgcli* command line tool, while *QGIS 3.4 LTR©* is used for data query and visualization.

PostgreSQL© is an object-relational database management system (ORDBMS) and is not a fully object-oriented system, but a set of object-oriented features is already available:

- Inheritance—generalization and specialization are fully supported.
- Support for complex objects and extensibility—custom data types and functions can be declared.
- Overriding—the same function can have different behaviours based on the input arguments.

Some other features are not natively implemented, but can be emulated with a few workarounds:

- Encapsulation and classification—these features can be emulated with custom data types for the attributes, and custom functions for methods.
- Aggregation—automatic aggregation based on class membership can be reproduced using PostgreSQL views and/or materialized views along with PostGIS aggregate functions like *ST_Union* or *ST_Collect*.

Lastly, object identity is not available as it is a concept strictly related to the object-oriented paradigm and as such, it is a feature only available in fully object-oriented languages and there is no way to implement such feature in a RDBMS. As for now, objects are stored as table records.

The database has been structured into three main blocks: a dictionary block, a data block and a visualization block. In the dictionary block, tables containing reference terminology are included. The main purpose of this data is to prevent errors during the process of data entry, therefore, to maintain data integrity. These tables are accessed through foreign keys by tables contained in the data block and by some of the dictionary tables themselves. Terminology contained in this block is about landslides (Hungr et al. 2014) and spatiotemporal topology semantics (Allen 1983; Egenhofer and Herring 1990b; Randell et al. 1992). The defined tables are as follows:

- Landslide material types, containing reference information about landslides material.
- Landslide movement types, containing reference information about landslides movement type.
- Landslide types, containing reference terminology about landslide types, this table also refers to the material and movement type tables.
- Topological predicates, containing predicates for the RCC8 topological model and their corresponding matrixes for the DE9IM topological model.
- Temporal predicates, containing Allen’s predicates for temporal relationships.
- Spatiotemporal predicates, containing spatiotemporal predicates, this table also refer to the RCC8 and temporal table.

The data block is structured to contain the instances of the object-oriented model. Here, a table is defined for every class declared in the model, meaning that the final result will be having 21 tables for *landslide subobjects* plus 1 generalized landslide table, 21 tables for *landslide complex subobjects* plus 1 generalized landslide complex table and one table for landslide systems.

In the visualization block, objects from the data block are rearranged for the correct visualization. The vertical sorting is applied using the temporal characterization of landslides and the overlap index. This process only applies to components, landslides and complexes, landslide systems, as for their definition, do not overlap, thus do not need vertical sorting.

Application to the case studies and results

The presented data model and structure has been applied on two selected test sites located in the Cilento UNESCO Global Geopark (Aloia and Guida 2012), southern Italy (Fig. 2).

The first investigated area corresponds to the south-western slope of Mt. Pruno (879 m asl), which is the highest relief of the Roscigno municipality (WGS84 40° 24′ 42.68″ N, 15° 21′ 46.44″ E;

Google Maps). The main morpho-structure is a hilly relief culminating in the main hill ridge, constituted, in the upper-slope, by an arenaceous-pelitic, stratified, slightly folded sequence, that, in the mid-slope, overthrusts on a strongly deformed and sheared, predominantly pelitic sequence. The relevance of this case study is mainly due to the connection between repeated landsliding and cultural heritage for sustainable local development. Over the historical times, two human settlements were affected by gravity-driven processes, inducing twice their complete abandonment. In turn, the present-day villages and infrastructures are highly threatened by active, endemic landslides, causing difficulties in touristic connections. The ancient Enotrian settlement, build-up on the flat top of Mt. Pruno, now an interesting archaeological site, and the Old Roscigno village, now a visited *ghost town,* located in the middle slope, are both two great examples of cohabitation between anthropogenic activities and landslide processes. The Old Roscigno village has been involved in a deep-seated, reactivated, landslide processes at least from the second half of the XIX century and was abandoned in 1964 (Catenacci 1996). Following Calcaterra et al. (2014), the Enotrian settlement on the upper slope was involved by an early, retrogressive reactivation of the same gravity-induced deformation, that could be traced back to the III-IV century B.C, acting on pre-existing, Holocene landslide systems.

The second case study is focused on the fast slope movements affecting the cliffs overlooking the Morigerati village (WGS84 40° 08′ 32.4″ N, 15° 33′ 28.2″ E; Google Maps), well known as *village-hotel*, supporting the visiting people at the Otter WWF Oasis, along the Bussento karst Resurgence gorge (Valente et al. 2020). The morpho-structure results from a series of south-dipping, normal faults, which produced the lowering of thick-bedded limestones and inter-bedded marly-clayey horizons and the creation of fault-line slopes. Rock falls and topples from retreating free faces are a constant threat both for the settlements and touristic sites located along the backslope and footslope. Boulder and block deposits accumulated at the base of the free face can evolve in time as block debris avalanches and channelized dry debris flows.

The space-time landslide inventory was derived from previous data collection, both from regional inventories (PAI (Campania River Basin Authority Plan for Hydrogeological Risk)) and specific inventories from scientific commissions (C.U.G.RI. (Interuniversity Consortium, called Centre for the Prediction and Prevention of Great Risks, at the Salerno University)), integrated with original and un-published field surveys carried out by the authors (January–June 2015, July 2016 and July 2017). Landslide data from existing inventories have been then updated following the above LOOM data structure and the latest, inventoried landslides have been coherently integrated.

At the Mt. Pruno case study, the main feature affecting the slope is a rock slope deformation that is the prominent feature which caused the abandonment of the Old Roscigno village. Within the LOOM data structure, for its type, this movement falls within the *deep-seated slope deformation class*, therefore, it is a *deep-seated slope deformation object*, or rather a specialized *landslide object*. Its components, such as the main trench, are still visible in the village, where several buildings are tilted or damaged. On top of the deep-seated movement, several shallower phenomena developed, like clay rotational slides (*soil rotational slide objects*) and soil creep movements (*shallow slope deformation objects*). From the top of Mt. Pruno, also a few clay rotational slides-earth flows reach the upper portion of the rock slope deformation. Following the LOOM data model, all these features have been inventoried as single *landslide objects* with their own descriptive, spatial and temporal attributes. Compiling the *landslide objects* dataset, the *landslide complex objects* and the *landslide system objects* datasets automatically update to store aggregated objects based on the defined rules for aggregation. As a result, most of the *soil rotational slide objects*, as for their spatial relations, have been aggregated in *soil rotational slide complex objects*. Moreover, most of these movements have been further aggregated in a *landslide*

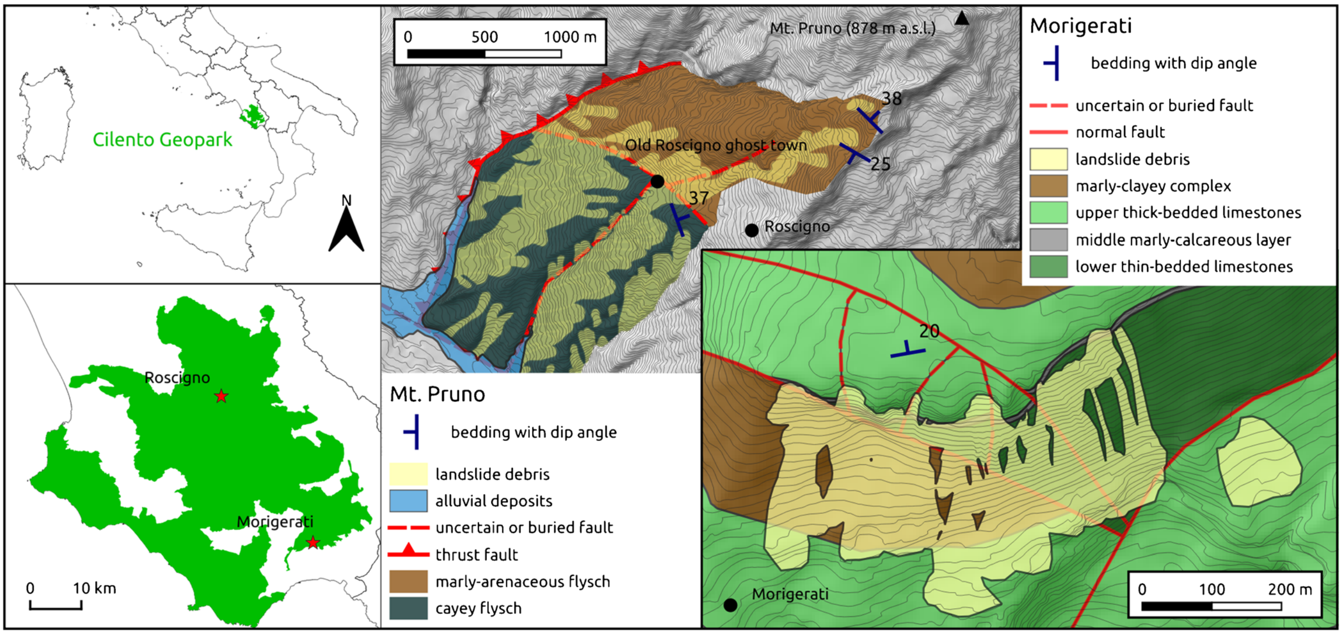


Fig. 2 Case studies location, geological settings and landslide-affected areas

system object, which, compared to the main *deep-seated slope deformation object* described before, is 0.5 km^2 larger.

On a temporal perspective, the oldest recognized process is the basal rock slope deformation, which experienced its last noticeable acceleration around the second half of the 1800 and the first years of 1900. Other movements on top of the deep-seated deformation, may have experienced their first activation even before these dates and then being passively carried down valley by the deeper deformation, but they, for certain, experienced further reactivations through the last century to present days, as demonstrated by several deformations along the local road network. This is to say that the last acceleration of the deep-seated slope deformation can be considered as the first recognizable event for this landslide system, as we have no information about previous movements. After this event, the hillslope experienced several shallower phenomena such as rotational slides, coupled with shallow soil creep, with various overlapping degree, some of which are responsible for the latest damages to the Old Roscigno village and its final abandonment (Fig. 3).

Morigerati cliffs, instead, are mainly affected by rock falls and rock topples which have been stored in their respective classes, referring to their single detachment and translation traces and/or their cumulative accumulation areas. Sometimes, debris from previous events, accumulated as apron or scree at the free face base, are remobilized as debris avalanches, these movements fall within the *granular soil wet flow class*, thus have been stored as *granular soil wet flow objects*. Collapses of metric-sized limestone boulders have been also observed. These phenomena originated from previous rock falls or rock topples debris and they are mainly due to the erosion of the marly-clayey soil beneath them, causing the retreat of the free face. Using the LOOM classification scheme, these movements have been inventoried as *soil fall objects*. Following the aggregation procedure, the series of *rock fall objects* sharing a functional interaction have been aggregated into *rock fall complex objects*, just two of them (the easternmost and the westernmost ones) remain as *isolated rock fall objects*, as they do not share any functional interaction with any other object of the same class. Besides rock falls, one *granular soil wet flow complex object* and one *soil fall complex object* are generated. In the last aggregation step, the landslide system existence is verified. As a result, almost all the inventoried objects can be aggregated in a *landslide system object*. Referring to the previously cited *isolated rock fall objects*, the westernmost one is part of the landslide system, as it shares a functional interaction with a *rock block topple object* and a *soil fall complex object*, while the easternmost one cannot be aggregated as it does not share any functional interaction with any other object, thus it is not part of the *landslide system object*. The temporal sequence of events clearly depicts the hillslope evolution: first, rock falls and rock block topples occur as a result of the combined action of rock mass joints enlargement and karst processes, then the resulting deposits are remobilized as debris avalanches or rolling boulder falls (Fig. 4).

Discussions

The proposed object-oriented model for landslides allows storage and preservation of spatial and temporal relations between *landslide objects*. In this object-oriented approach, the landslide inventory is built preserving spatial relations so that every inventoried landslide is stored entirely, with no cut portions, and its topological connections can be easily retrieved by queries. Overlapping and nested landslides are then handled with the hierarchical classification, which leads to the simplification of the history of gravity-induced instabilities on a hillslope into one superlandslide object, being it a complex or a system, depending on the movement types involved. Moreover, temporal attributes ensure the vertical sorting of the

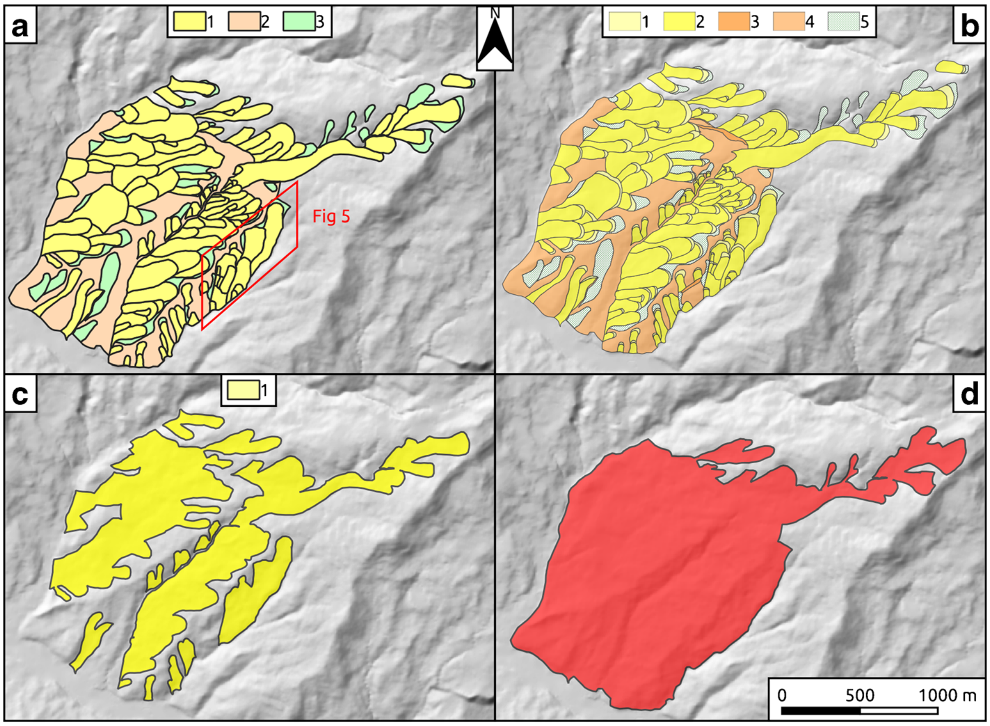


Fig. 3 Landslide maps for the Mt. Pruno case study: **a** Focal level—landslide objects, (1) soil rotational slide objects, (2) deep-seated slope deformation objects and (3) shallow slope deformation objects (the red box highlights landslides shown in Fig. 5); **b** level − 1—landslide component objects, (1) soil rotational slide detachment area objects, (2) soil rotational slide body objects, (3) deep-seated slope deformation trench objects, (4) deep-seated slope deformation body objects and (5) shallow slope deformation objects; **c** level + 1—landslide complex objects, (1) soil rotational slide complex objects; and **d** level + 2—landslide system objects

mapped objects for the visualization of the dataset. Besides, temporal characterization allows to perform temporal queries on the dataset. This, along with the implementation of temporal paradigms, evolve common GIS applications to the level of T-GIS. Referring to the Old Roscigno case study, the proposed approach allowed the reconstruction of the landsliding history that affected the village. From the analysis of spatial and temporal relations between the movements affecting the village result that *above* the deep-seated slope deformation object, several *younger* and mutually *overlapping* soil rotational slide objects developed. The last can be aggregated in a soil rotational slide complex object which is responsible for the last damages to the settlement causing its definitive abandonment. Both the deep-seated slope deformation object and the soil rotational slide complex object are part of a larger landslide system object which extends almost from the top of Mt. Pruno to the valley. The Morigerati case study, instead, is an example of how such data structure gives useful insights on the geomorphological evolution of the investigated area, just querying for the temporal succession of different process types.

Within an ideally complete dataset built with the LOOM data structure, executing temporal queries allow to retrieve various useful information, such as snapshots of the slope at any time period, landslides occurred in a specific time frame, temporal relations between landslides, helpful for investigating cause-effect relationships, or the number, hence the time-series of events that affected the slope, essential for magnitude/frequency analysis. All of these operations allow the production of the same mapping outputs described for current inventorying approaches. Querying for the state of a slope at a specific time period results in the production of a static landslide map, while asking for the same output but for different time periods, produce a series of snapshots of the slope gravitational history. In the same way, it is possible to retrieve landslides which occurred in a specific time frame or triggered by a specific event, producing time frame or event maps (Fig. 5). However, in order to perform spatial and temporal analysis, the dataset should be as complete as possible. Completeness implies spatial and temporal accuracy: whereas the first can be achieved with a meticulous mapping of present-day features, the second can be quite challenging. Reconstructing the temporal evolution of a slope means collection of features that may no longer be visible today. This task can only be performed consulting pre-existing material such as previous inventories, optical images both aerial and satellite, previous maps, or historical data, as well as morpho-chronological analysis. All of these operations, unfortunately, are time-consuming and difficult to perform over large areas; moreover some areas may lack of previous information (Guzzetti et al. 2012). In such cases, building an inventory using the proposed object-oriented model can be an efficient starting point to store presently available data ready to be easily updated with future occurrences. On the other hand, previous multi-temporal inventories, when available, can easily be rearranged following the object-oriented model. Converting snapshot-based datasets into one temporal dataset reduce data redundancy, thus data volume, in fact if the same landslide is part of different snapshots and has not experienced reactivations, can be simplified into one landslide object with the proper temporal collocation.

This model allows the automatic aggregation of landslide objects into superobjects when the required criteria are met, simplifying such situations where an operator is faced with superimpositions/substitution of several landsliding events. Spatial relations between landslide objects also contribute to the definition of the number of interacting phenomena and their relative position in space, such information is indeed

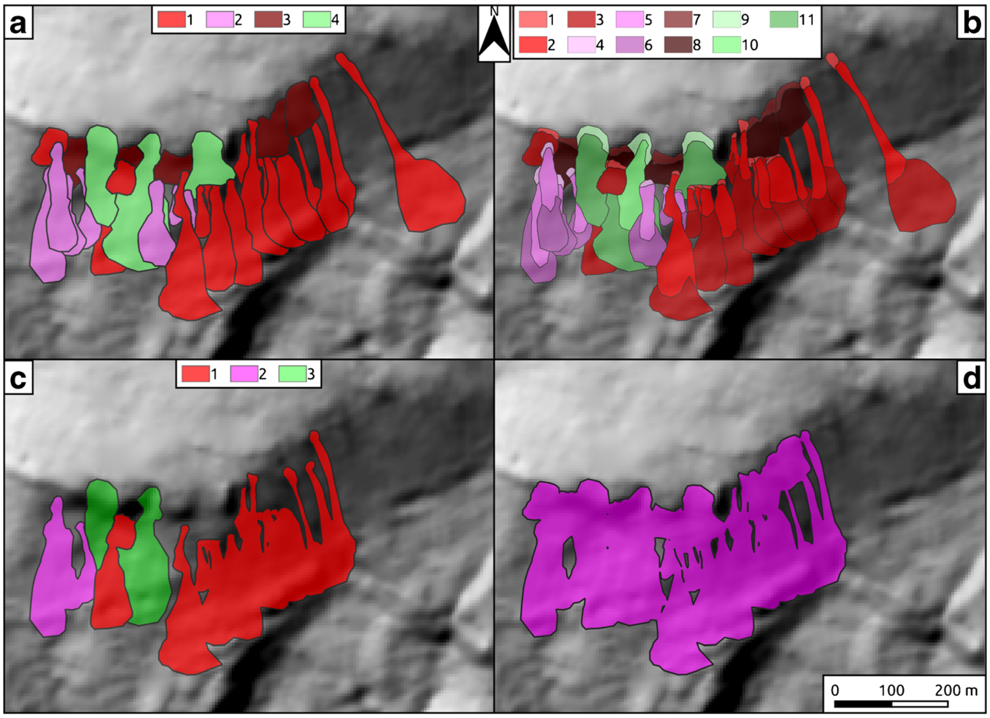
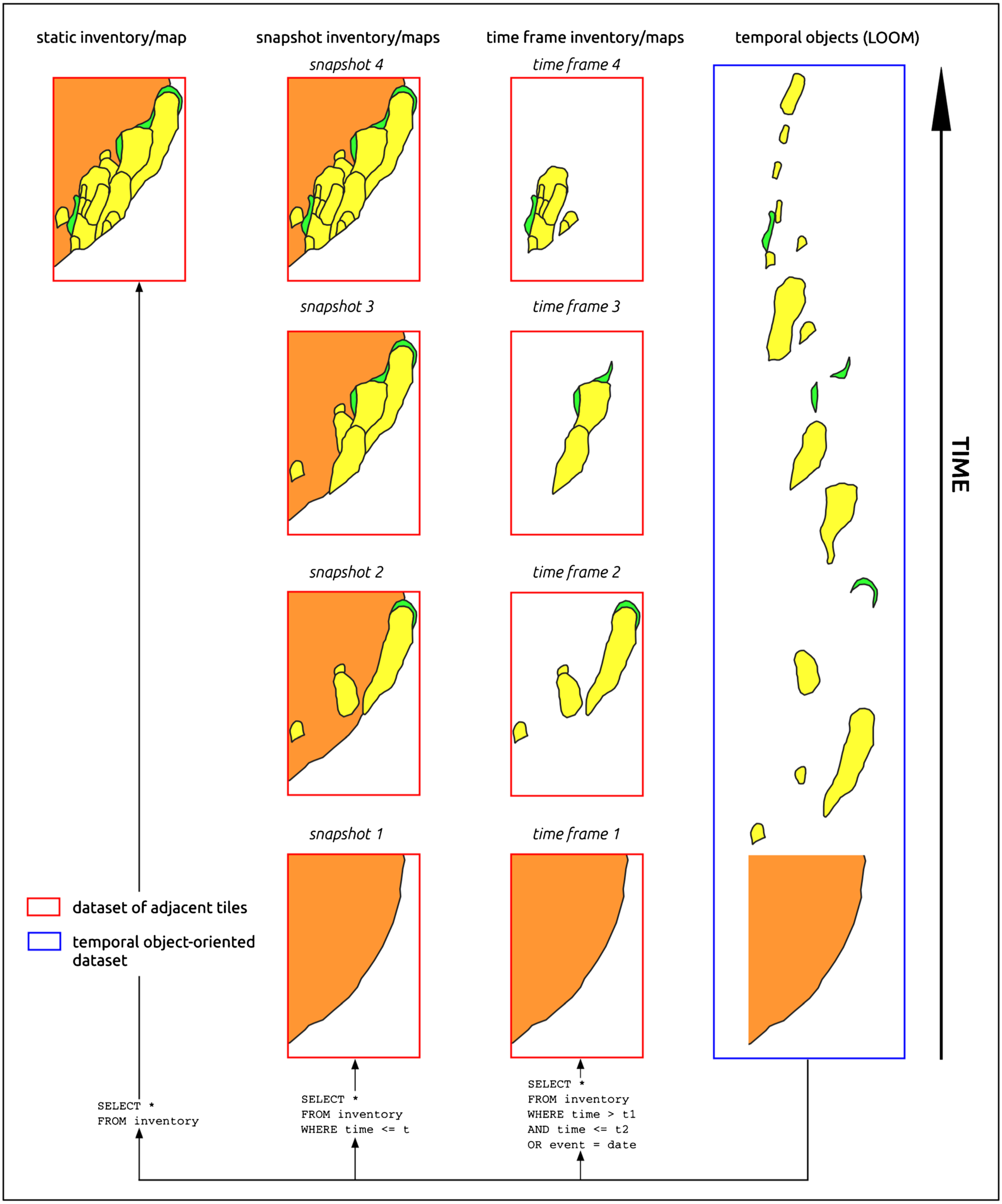


Fig. 4 Landslide maps for the Morigerati case study: **a** focal level—landslide objects, (1) rock fall objects, (2) soil fall objects, (3) rock topple objects and (4) granular soil wet flow objects; **b** level − 1—landslide component objects, (1) rock fall detachment objects, (2) rock fall transit objects, (3) rock fall debris objects, (4) soil fall detachment objects, (5) soil fall transit objects, (6) soil fall debris objects, (7) rock topple source objects, (8) rock topple debris objects, (9) granular soil wet flow source objects, (10) granular soil wet flow transit objects and (11) granular soil wet flow invasion objects; **c** level + 1—landslide complex objects, (1) rock fall complex objects, (2) soil fall complex objects and (3) granular soil wet flow complex objects; **d** level + 2—landslide system objects



```
SELECT *
FROM inventory
```

```
SELECT *
FROM inventory
WHERE time <= t
```

```
SELECT *
FROM inventory
WHERE time > t1
AND time <= t2
OR event = date
```

Fig. 5 Comparison between usual approaches at multi-temporal landslide inventories (red boxes) and LOOM data structure (blue box) (refer to Fig. 3 for landslides types and location); on the bottom: simplified queries used to derive usual maps starting from LOOM data structure needed to determine the spatial extent of a deformation area and infer its volume by boreholes or geophysical surveys. The obtained set of information consequently affects the concept of landslide hazard. If several landslides interact, their level of hazard should not be defined just for each object but should be related to the other interfering phenomena. Moreover, when a landslide is part of a landslide complex and/or of a landslide system, different levels of hazard should be defined for the different hierarchical levels. At the present time, these aspects with regards to hierarchical objects and their associated hazard have not yet been investigated and the presented model sets the basis for future works inherent this topic. However, defining that a landslide is part of a larger landslide system can be not always the final answer for every problem; in fact such a system may be composed of objects evolving on long-term which may not affect considerably, or not at all, the objective of a particular study. In this perspective, further efforts are also needed in order to characterize the landslide hierarchical levels in relation to engineering works, to be able to quantify the interactions between landslides and anthropogenic activities at the different scales and to effectively plan and design intervention strategies.

Conclusions

This work describes the development and the results of preliminary applications of an object-oriented model for landslides. Complex spatiotemporal arrangements of landslides are handled through an object-oriented classification and a hierarchical organization of objects based on rigorous topological relations. The focal level of the hierarchy is set containing landslides themselves, classified depending on their movement type, and two orders of superclasses are defined: (i) landslide complexes aggregate landslide member of the same class with functional interaction, i.e. spatial overlap, and (ii) landslide systems group landslides or landslide complexes members of different classes sharing a functional interaction. Instead, a level of decomposition stores landslide components, such as detachment areas and bodies. Landslide objects are also characterized with temporal attributes using a combined time frame- and event-based approach, essential for the temporal-vertical sorting of phenomena and to perform temporal queries.

Results show how the object-oriented classification can be a powerful model to derive landslide hierarchies and manage complex spatiotemporal succession of landslides. Encapsulating all spatial and temporal relations between landslides within the definition of a landslide complex or a landslide system, also avoid physical data fragmentation and logic inconsistency, as topology of data complies with topology of real-world features and vertical relations are preserved.

The defined model has been implemented using the object-relational database management system PostgreSQL, which, although not being fully object-oriented, allows reproduction of some basic functions as aggregation, encapsulation and overriding using views, custom functions and custom data types. Such implementation allows automatic organization of inventoried phenomena into hierarchies, defining landslide complexes and landslide systems, providing a powerful tool to manage the natural complexity of the spatiotemporal superimposition of several landsliding events. The implementation of temporal analyses in a GIS allows the user to retrieve useful information over a landslide dataset, such as the number of events that affected a hillslope, the number of reactivations for a single movement and temporal snapshots of the slope at any recorded time period. The temporal succession of interacting landslides also describes the past evolution of a slope helping the formulation of future reactivation/repetition scenarios. Such temporal analysis requires that the landslide inventory is built on a collection of multi-temporal information from a variety of sources. Sometimes such data are not available; in that case, using an object-oriented model can be both a starting point to best represent actual conditions and a base dataset ready to store future updates.

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