Technical and organizational challenges in the risk management of road infrastructures

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Abstract

This paper outlines a theoretical framework for the risk management of road infrastructures from the perspective of organizational studies and engineering science. The framework moves beyond the traditional approach analysing each road infrastructure in isolation, and adopts the emerging systemic approach aimed at optimizing the interrelation between infrastructures, while at the same time extending this approach by considering actors as well as infrastructures. The initial focus is on the interaction between the parts (infrastructure and related actors) within a system (infrastructure and related actors within administrative boundaries) with a focus on two organizational modes: coordination and fragmentation. The choice between coordination and fragmentation depends on the span of safety and the level of risk. Furthermore, coordination and fragmentation offer useful insights for decision-makers by addressing specific modes of governance aimed at avoiding a lack of cooperation and ineffective responses. The paper then examines satellite data obtained from differential interferometric synthetic aperture radar (DInSAR) in a geographical information system (GIS) platform. The aim is to identify the span of safety within a system, concerning specific infrastructures with the related actors, and to assess the risk levels for road infrastructures. The approach is intended to identify the most appropriate organizational mode. The potential of this approach was tested in a sample area of Rome (Italy), and the results reveal a significant span of safety with a common negligible risk, and a subspan of safety with a moderate risk. In the first case, coordination between the parts is desirable. As a result, long-term and fully shared solutions can be adopted, including joint planning operations and standard operating rules. In the second case, fragmentation is indicated, with more flexible solutions characterized by sharing and local autonomy.

Keywords: infrastructure risk management, coordination/fragmentation, span of safety, level of risk, DInSAR monitoring.

1. Introduction

Road transport infrastructures (e.g., bridges, viaducts, highways and roads) are attracting significant security and safety criticisms due to human and natural hazards, respectively. In fact, human and natural hazards have frequently led to a loss of functionality and, in extreme cases, infrastructure collapse with natural, social and economic consequences (Mansour et al. 2011; Argyroudis et al. 2020). Infrastructure safety management is thus a priority for public authorities, road agencies and private operators, giving rise to the need for risk assessment.

In risk assessment, there is a discrepancy between increasingly complex analytical approaches and the scale of the investigation. Risk assessment tends to take the form of plans, strategies and studies. However, the spatial dimension of risk assessment is often geographically limited. Planning authorities typically adopt a complex approach to risk assessment, considered from a physical, economic and social point of view. By way of example, bridge management systems, developed in road infrastructure risk management, are commonly based on a complex strategy adopted by public and private agencies in which the tools for the maintenance, repair and rehabilitation of structures take account of environmental, economic and social factors (Decò and Frangopol 2011). In addition, this complex approach to infrastructure management goes hand-in-hand with the comprehensive approach increasingly taken by studies dealing with the broad spectrum of risks. This creates a continuum from research to the development of land-use policy and vice versa.

In connection with road tunnel safety, Kazaras and Kirytopoulos (2014) propose a mixed methodology integrating a quantitative risk assessment model with qualitative models taking into account organizational aspects, system accidents, software behavior, and the human factor.

Thekdi and Chatterjee (2018) analyse the resilience of distributed infrastructure systems investigating the role of multiple direct and indirect performance measurements. The methodologies adopted tend to reflect the needs of land-use planners and policy-makers (Saidi et al. 2018). Moreover, Zhou et al. (2014) carried out an integrated risk analysis for gas pipelines aimed at sustainable land-use safety planning and governance. Furthermore, Linthicum and Lambert (2010) examine the risk assessment of land development adjacent to infrastructure corridors based on expert elicitation and geographic data with the aim of providing guidance for planners.

Other studies have combined bridge management systems with structural health monitoring to develop monitoring systems to measure the structural response in real time, in order to detect anomalies and damage at an early stage, aiming at a more efficient risk management policy (Figueiredo et al. 2013; Celebi 2007; MIT 2020).

Although the approach adopted in these studies tends to be comprehensive, the spatial dimension of risk analysis is often geographically limited. This reflects the aim of public and private actors to focus risk management[1] on specific road infrastructures within their jurisdictions or under their management.

Traditional studies are based on the idea that each road infrastructure should be analysed in isolation (Wu et al. 2015), thus leading to non-standardized assessment methodologies (e.g., content analysis, surveys, probabilistic or deterministic analysis). However, some systemic analyses of various kinds of infrastructures highlight the fact that they are interdependent and part of a wider system (Dudenhoeffer et al. 2006). If road transport infrastructures are considered in isolation, this fails to take account of the fact that most of them are functional to other infrastructures (e.g., industrial activities) as well as being physically connected to other critical infrastructures (e.g., gas pipelines, electrical lines), or supported by other infrastructures, albeit managed independently. As a result, they are highly interdependent as they are subject to common factors, such as the risk of failure due to ageing, economic/population growth, extreme natural or human events, and climate change (Troisi and Alfano 2019).

Although the term “systemic” is used in studies dealing with civil infrastructure as a synonym for holistic, it tends to focus on the concept of interdependency to construct effective models, focusing on the relationship between the state of the infrastructures and their mutual influence (Rinaldi et al. 2001). This means that it is characterized by a level of detail that is not representative of a more comprehensive systemic approach (Saidi et al. 2018), where on the other hand individual elements concern both infrastructure and the actors responsible for infrastructure management.

To overcome these limits, this paper brings together organization theory and engineering science to focus on the interaction between parts rather than the interdependence between infrastructures. This systemic approach is intended to clarify the kind of interaction that is necessary between the parts. According to organization theory, interaction can be achieved by means of two organizational modes: coordination and fragmentation. Hence, the question addressed in this paper is when and how risk management requires coordination or fragmentation within an infrastructure system.

First, a theoretical framework is outlined that is intended to emphasize the nature of a system and then explain the choice between coordination and fragmentation as a result of design and contingency. The span of safety and the level of risk determine whether coordination is required, bringing all or most of the parts together in a cohesive manner, or whether fragmentation

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[1] The concept of “risk management” is considered in broad terms to include maintenance and intervention plans and strategies.

would be more appropriate focusing on specific parts (i.e., specific infrastructures within a wider system).

Furthermore, coordination and fragmentation can provide useful insights for decision-makers by addressing specific modes of governance aimed at avoiding ineffective responses, while favouring cooperation on a local scale.[2]

Second, the theoretical framework needs to be combined with a technique to monitor road infrastructure systems (i.e., network systems) with a local analysis, instead of focusing exclusively on one specific infrastructure (Bocchini et al. 2014). In the present study the analysis of the span of safety and level of risk in terms of choosing between the two organizational modes within a systemic analysis entails the adoption of the differential interferometric synthetic aperture radar (DInSAR) technique (Crosetto et al. 2016). This technique employs the data acquired by means of a satellite constellation (e.g., the Italian COSMOSkyMed satellite constellation), known as a deformation time series. In addition, the satellite data can be used to assess any displacements of the infrastructure due to various hazards (e.g., earthquakes, slow landslides, seasonal changes, temperature effects, subsidence phenomena, soil-structure interaction phenomena, degradation phenomena of structural components) on a local scale (Fell et al. 2008). The DInSAR data are then imported into a geographical information system (GIS) platform to be georeferenced with respect to the local area and further managed in the same digital environment. In this way, risk maps are created for the road infrastructures, adopting a hybrid method (Török et al. 2020).

The satellite-based local scale analysis makes it possible to identify the span of safety connecting the infrastructures with the related actors. In addition, it is possible to assess the risk levels for road infrastructures, and choose the most appropriate organizational mode within a systemic analysis. In the present study, to show how the theoretical framework supported by the DInSAR technique can lead to improvements in the risk management of road infrastructures, it was decided to test the approach in an area with about 1600 kilometers of road transport infrastructures in and around Rome (Italy). The results highlight how this approach provides an in-depth understanding of the interaction among the parts within a system, thus offering a useful support for policy-makers. The technical results show a large span of safety characterized by a common negligible risk, and a subspan of safety with a moderate risk. In the first case, the coordination between parts is desirable. This means that long-term and fully shared solutions can be adopted such as joint planning, rules and standard operations. In the second case, fragmentation is required: more flexible solutions combining sharing and local autonomy can follow.

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[2] The term “local” is used to identify an analysis scale or a geographical area within administrative boundaries (e.g., regional or sub-regional).

The reminder of the article is structured as follows: Section 2 outlines the theoretical framework. Section 3 provides details of the DInSAR and GIS techniques and describes how to combine the techniques with the theoretical framework. Section 4 introduces the case study, and discusses the results, whereas Section 5 summarizes the conclusions.

2. Theoretical Framework

In its most basic sense, a system is a set of elements together with the interactions between the elements and their attributes. Organizational studies have widely investigated the way in which a system is arranged (Fjeldstad et al. 2012) and developed an approach based on three key concepts. First, the setting of a complex system is rooted in the concept of modularity, or decomposability, where the level of decomposition depends on the need for interaction between elements aimed at achieving a given result (Simon 1961). In such a system, the interaction between the parts can concern two, some or all parts of a system. Second, the interaction between the parts is a combination of design and contingency. Coordination is an organizational mode that brings all or most of the parts together in a cohesive manner. On the other hand, in the case of fragmentation, the focus is on specific parts within a system. The choice between coordination and fragmentation depends on the level of performance required (Faraj and Xiao 2006). Third, the choice of either coordination or fragmentation depends on a set of factors that shift continuously, adapting to the kind of objective to be achieved.

It may be argued that risk management of road infrastructure systems should be approached through the two main modes of organization, with the choice depending on the span of safety and the level of risk (Künneke et al. 2010). For the sake of simplicity, the infrastructure systems are clustered within administrative boundaries (e.g., regional or sub-regional). Depending on the administrative boundaries (i.e., local scale), the elements of a road infrastructure system may be subject to change.

1) Span of safety: this dimension brings together interdependent road infrastructures and the related actors. The main measure of their interdependency is geographic (Zimmermann 2004). A common geographical location is important for safety issues for two reasons. The safety issues of one infrastructure asset may have domino effects on other infrastructure assets located nearly, or an environmental event can impact all the infrastructures in the vicinity. Furthermore, geographic interdependency can be strengthened with functional interdependency when the roads share a connecting function, in the sense that they connect the origin and destination areas; when they share a collecting function within origin-areas, and distribute within the destination

areas; and finally when some roads act as links for those in a higher class. They thus have a similar traffic flow, similar traffic capacity, or similar travel speed (Lauwers 2008). As a result, the most extensive span may cover the entire system at a local level (e.g., regional and sub-regional) with the nodes and links of the network characterized above all by geographical interdependency. A less extensive level could be described as a subsystem characterized mainly by functional interdependency considering a technically separable part of the overall system. The subsystem performs certain services independently from the overall system. For example, within a system, the primary and secondary road network is strongly connected as a network of express roads with similar characteristics, distinct from other roads. At the lowest level, a limited number of road infrastructures in close geographical proximity constitute a sub-group, since their proximity increases the likelihood that they will be affected by the same specific issues. However, they can also be functionally interdependent. This level is attainable, especially for particular cases, for roads within the same industrial area.

Although the span of safety mainly concerns road infrastructures, it also makes it possible to identify the specific actors involved due to their jurisdiction over or management of road infrastructures.

2) Level of risk: this plays a crucial role in the interaction between road infrastructures and consequently the actors involved at a given local scale. The level of risk is relevant as it determines the timeframe needed to tackle safety issues and the priority of interventions among actors. Generally speaking, the higher the risk, the more rapid the intervention. Moreover, the higher the risk associated with one or more road infrastructures within a sub-group, subsystem or system, the higher the priority of intervention.

   Organizational studies add some arguments in terms of the kind of activities that work best depending on the level of risk. A high level of risk requires greater flexibility in terms of speed and also to deal with the discontinuity and uncertainty that characterize high-risk events (Thompson 1967; Wall et al. 2002). On the other hand, low levels of risk are best handled by means of standardized processes that minimize uncertainty as low risk does not require rapid interventions, nor does it reach the degree of ambiguity of high risk.

These two dimensions jointly determine whether coordination or fragmentation is required. Coordination between the parts tends to be required for systemic, sub-systemic interaction where interdependent road infrastructures are affected by negligible, very low or low risk situations (see *infra* – Section 3.2). In such cases, all or most of the actors can be involved as there is sufficient time for joint management.

In these conditions, coordination can be accomplished by means of different modes of governance. Actors can adopt common rules and standard operating procedures, or choose market competition for the most suitable technical solution, which can be jointly funded.[3] Finally, they can adopt common land-use planning for the enlargement of road infrastructures since the low level of risk enables medium- to long-term projects to be implemented.

Fragmentation is the best option in systems and subsystems with specific subsets in two situations. In the first, interaction concerns infrastructures that are at least geographically interdependent, in cases where they are characterized by very high, high or moderate risk (see *infra* – Section 3.2). In the second, interaction concerns functionally interdependent infrastructures with different levels of risk: some are affected by very high, high or moderate risk (see *infra* – Section 3.2) while others are characterized by a lower level of risk.[4] In the first case, the road infrastructures characterized by imminent risk require separate management with higher priority than road infrastructures with a lower risk. In the second case, the close functional interdependency between infrastructures increases the probability that any disturbance will spread rapidly across them, thus requiring a focused management, with a priority of intervention determined according to risk.

The need for fragmentation can be met in these conditions by means of different modes of governance that are "loosely coupled" (Perrow 1984). These modes of governance can ensure flexibility in creating specific solutions. They can adopt shared objectives and provide a certain amount of leeway in their implementation, while some measures can be determined through a process of mutual adjustment and implemented on the basis of standardized procedures.

Under these circumstances, collaborative intervention can be aimed at planning specific measures for public safety. By way of example, they can be aimed at modifying road layouts or building engineering works in the surrounding environment as a means of protection against hazards. Additional urban planning interventions include public or private constructions close to road infrastructures by defining safe distances within the urban context.

3. DInSAR technique-based risk maps in a GIS environment for systemic analysis

This section offers insights into the techniques associated with the theoretical framework. Section 3.1 focuses on the main technical features of DInSAR satellite monitoring and provides details of

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[3] Among all the possible combinations, the ones that are realistically possible are highlighted.

[4] Fragmentation is excluded in the case of a common low level of risk affecting a limited number of infrastructures (i.e., sub-group) since there are no specific scale advantages in comparison to one-off interventions.

the risk assessment within the GIS environment. Section 3.2 explains the alignment of the techniques with the theoretical framework.

3.1 DInSAR and GIS techniques aimed at local risk assessment

The DInSAR technique is widely employed to observe the Earth’s surface using satellites. It exploits the phase difference of at least two complex-valued SAR images. Images are acquired by sensors placed in the Lower Earth Orbits (LEO), between 500 km and 800 km from the Earth, following polar orbits in order to provide global coverage. Accordingly, images may be obtained by SAR sensors over the ascending and descending orbits, typically in opposite directions in relation to the ground. There are several multi-pass DInSAR algorithms that retrieve information about the displacements of the topographic surface (Berardino et al. 2002; Mora et al. 2003; Kampes and Adam 2005; Fornaro et al. 2007).

The accuracy of the DInSAR data mainly depends on the coherence, that measures the agreement between the data and the algorithm used in the analysis with values between 0 and 1 (PST-MATTM 2010). Other factors such as the wavelength, number of images, overall temporal span, and the confidence level of the processing algorithm are also relevant (Peduto et al. 2015). It has been demonstrated that accuracy varies from 1 to 2 mm/year for the average velocity and in the range 5-10 mm for the single displacement time series (Colesanti and Wasowski 2006; Casu et al. 2006; Herrera et al. 2009).

The potential uses relating to DInSAR data have been demonstrated worldwide to detect, map and monitor ground displacements associated with natural or anthropogenic phenomena (Terrafirma 2013; PSTA-MATTM 2010, ReLUIS 2019-2021) at local level. The DInSAR technique presents three key advantages. First, SAR images have a high spatial coverage. Second, a large dataset of images assembled over several years makes it possible to measure ground surface displacements with sub-centimetric accuracy. Third, a large part of the geographical area with a significant number of buildings and infrastructures can be monitored at a lower cost compared to conventional in-situ techniques (Maroni et al. 2020; Maruccio et al. 2016).

The present study exploited these affordances in order to monitor the road infrastructures in a specific geographical area characterized by different hazards (e.g., earthquakes, slow landslides, seasonal changes, temperature effects, subsidence phenomena, soil-structure interaction phenomena, degradation phenomena of structural components). This technique is therefore particularly suitable for supporting a systemic analysis. In particular, the combined use of a GIS platform can be an effective way to represent data by means of thematic maps of the geographical area. In addition, by importing all the satellite data into the GIS platform, it is possible to georeference and process the satellite data for the purposes of risk assessment.

Data processing is as an essential part of risk assessment (De Mendonca and Gullo 2020; Fell et al. 2008; Schneiderbaue and Ehrlich 2006) as a function of the following terms:

- (H) hazard: expresses the magnitude of an event capable of causing damage within a given timeframe;
- (V) vulnerability: denotes the fragility of the exposed elements;
- (E) exposure: represents the number of elements exposed, whose value can be estimated in terms of costs as well as through classes or relative ratios depending on the functionality properties (Masi et al. 2021). When a road infrastructure system / subsystem with similar characteristics in terms of traffic flow or capacity or travel speed (Lauwers 2008) is examined, the related exposure is homogenous. As a result, in this specific case, “E” can be assumed to be equal to 1 and does not influence the risk assessment.

These three terms can be evaluated by means of a hybrid method (Török et al. 2020) based on deterministic or probabilistic criteria as well as qualitative and quantitative information, e.g., using correlations in the literature. In this study, the quantitative and deterministic DInSAR data relating to the hazard was processed, along with other quantitative and deterministic information relating to vulnerability assuming homogenous exposure. It was thus possible to define the corresponding hybrid risk maps of the overall infrastructure network system / subsystem at a local level. Finally, the DInSAR technique-based risk maps in a GIS environment were used to address the organizational issues in three phases, as follows.

3.2. Phases for aligning the technical and organizational issues

As shown in Figure 1, the use of the DInSAR and GIS techniques can be implemented in three phases to support the theoretical framework, as follows:

- *Identification phase*: the orthophoto (aerial photograph / satellite image) identifies the administrative boundary of the local area, and the road map identifies the infrastructure network and their interdependency. This makes it possible to identify the actors responsible for a section of road and the administrative authorities. The identification of systems and subsystems is transposed to the GIS environment by means of corresponding thematic maps. In terms of the theoretical framework, this phase concerns the span of safety.

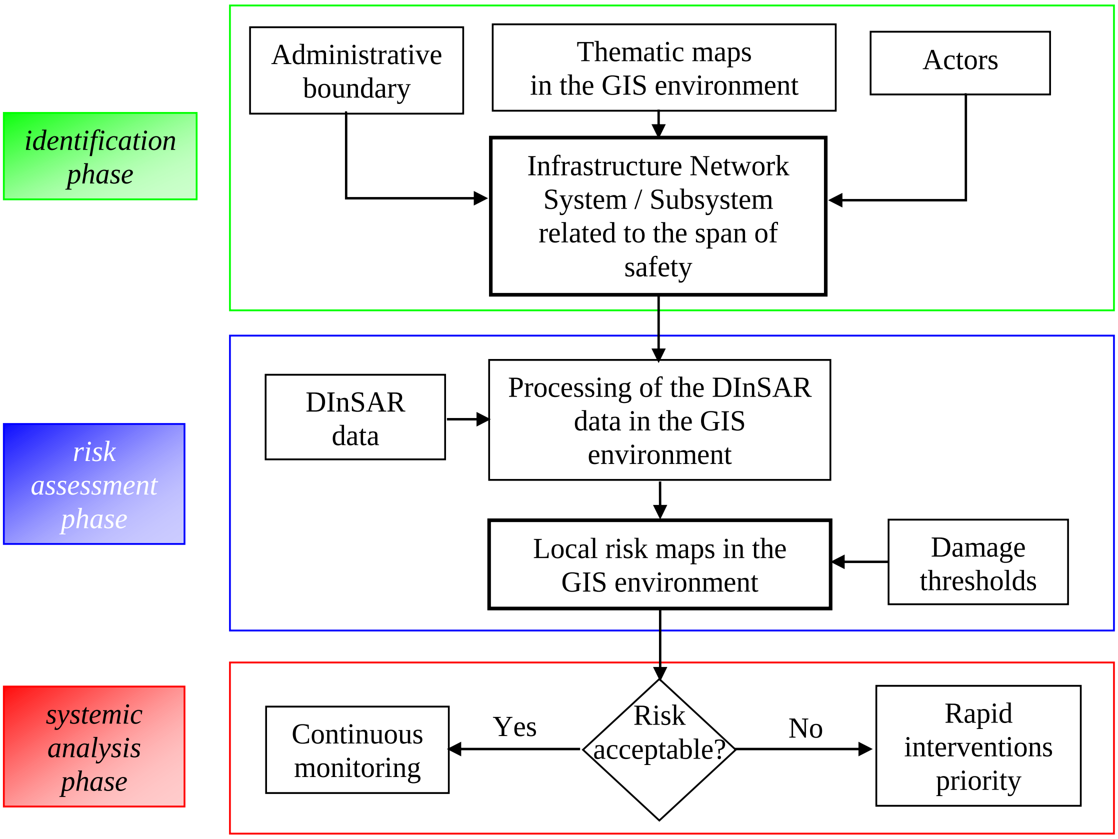

Figure 1. Flowchart of the three phases: identification, risk assessment and systemic analysis.

- *Risk assessment phase*: local risk maps are developed as outlined below and in the case study.

  The DInSAR data of both ascending and descending orbits are processed in the GIS environment to retrieve ground velocity/displacement measurements of the points over time. In particular, the system / subsystem of the infrastructure network is divided into cells to compute the Vertical (V) and East-West (EW) (i.e., Horizontal (H)) velocities, displacements and gradients. The horizontal and vertical gradients are then compared with the V and H damage thresholds, as shown in Tables 1-2. Six qualitative risk levels are then identified ranging from negligible to very high (Skempton and MacDonald 1956; Boscarding and Cording 1989; Castaldo et al. 2013, 2014). As a result, two risk maps of the infrastructure network are defined in the GIS environment. The maximum values between these two risk maps determine the risk level for each element of the infrastructure network under investigation. In terms of the theoretical framework, this phase concerns the level of risk.

Table 1. Damage thresholds in terms of vertical gradients with the associated levels of risk (Skempton and MacDonald 1956; Boscarding and Cording 1989; Castaldo et al. 2013, 2014).

Vertical gradient [-]	**Level of risk**
value >1/100	Very high
1/200< value <=1/100	High
1/400< value <=1/200	Moderate
1/500< value <=1/400	Low
1/750< value <=1/500	Very low
value =<1/750	Negligible

Table 2. Damage thresholds in terms of horizontal gradients with the associated levels of risk (Skempton and MacDonald 1956; Boscarding and Cording 1989; Castaldo et al. 2013, 2014).

Horizontal gradient [-]	**Level of risk**
value >0.5/100	Very high
0.5/200< value <=0.5/100	High
0.5/400< value <=0.5/200	Moderate
0.5/500< value <=0.5/400	Low
0.5/750< value <=0.5/500	Very low
value <0.5/750	Negligible

- *Systemic analysis phase*: a critical analysis of the system / subsystem is carried out. Specifically, for infrastructures characterized by unacceptable risk (i.e., from moderate to very high risk), the action required is based on both the rapidity and priority of safety interventions. For infrastructures characterized by acceptable risk (i.e., from negligible to low risk), monitoring is continued with a focus on prevention. In terms of the theoretical framework, this phase concerns the choices between coordination and fragmentation and, consequently, the most suitable modes of governance. Thus, it can support the decision-making process.

4. Case study: results

The theoretical framework, aligned with the DInSAR and GIS techniques, was tested in a sample area within the borders of the Municipality of Rome (Italy), as part of a research project (ReLUIS 2019-2021), as shown in Figure 2(a). The related road map was derived from “openstreetmap” and transposed into the GIS environment.

In line with the first phase (i.e., identification), from the general thematic map (Figure 2(a)), the relevant span of safety was extracted, consisting of a subsystem characterized by geographical and functional interdependency (Figure 2(b)).

Specifically, this road map focuses on an infrastructure network of 1600 km, consisting of highways, primary and secondary roads, according to “openstreetmap”. It represents the main traffic arteries within the municipal area, with both collecting and connecting functions and similar traffic flows. This means that the exposure is assumed to be 1.

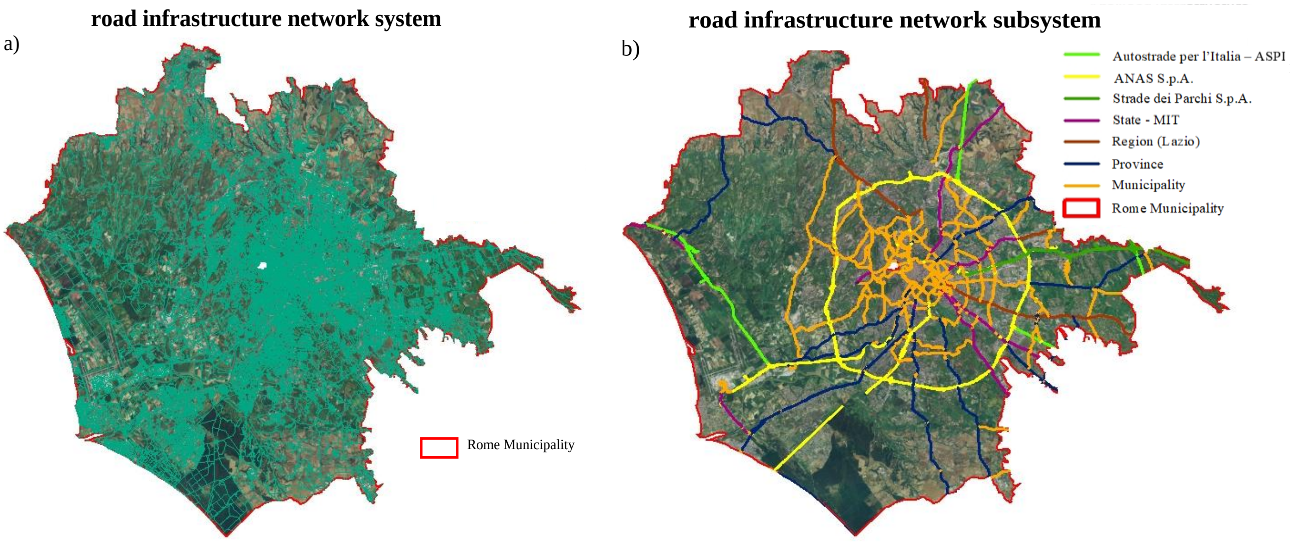

Figure 2. The road infrastructure network system (a); the road infrastructure network subsystem consisting of highways, primary and secondary roads with the corresponding actors (b).

Both public and private actors are involved in this subsystem (Figure 2(b)): AutoStrade Per l'Italia - ASPI, Strada dei Parchi S.p.A., ANAS S.p.A., State, Region (Lazio), the Provincial and Municipal administrative councils of Rome. In particular, AutoStrade Per l'Italia - ASPI is the largest highway agency in Italy and manages a network of about 3400 km, whereas Strada dei Parchi S.p.A. is another private company under the control of the Italian Ministry of Infrastructure and Transport. Finally, ANAS S.p.A. is an Italian government-owned company tasked with the construction and maintenance of several state highways (a network of about 26700 km) under the control of the Italian Ministry of Infrastructure and Transport.

In the second phase (i.e., risk assessment), local risk maps were created by processing data to identify the level of risk. The DInSAR dataset derives from the processing of the very high-resolution SAR sensor images (the Italian COSMOSkyMed satellite constellation) on both ascending (34° incidence angle) and descending orbits (29° incidence angle) to retrieve ground velocity/displacement measurements of the points. The dataset consists of 129 and 107 images on the ascending and descending orbit, respectively. The data timeframe ranges from July 2011 to March 2019 with a revisiting time equal to 16 days on average. Using a high coherence value of 0.6 (Yang et al. 2013), the study identified a total of 6,085,200 monitoring points on the ascending orbit (Figure 3(a)) and 8,131,283 monitoring points on the descending orbit (Figure 3(b)).

A specific mapping unit of pre-defined size (50x50m) was used to divide the area into cells in addition to the infrastructure network subsystem. The cell size was selected to reflect the dimension of a single infrastructure at a local scale (Calvello et al. 2013). Each cell is defined as "covered" if at least one measurement point (representative of a square of dimension of about 3m x 3m) falls within its perimeter, also considering localization error (Peduto et al. 2015). With regard to the infrastructure network subsystem, Figure 4 shows the cells covered by the DInSAR data acquired on the ascending orbit (2,404 cells with 5,105,749 monitoring points), on the descending orbit (2,312 cells with 3,793,425 monitoring points) together with those covered by both orbits (2,008 cells).

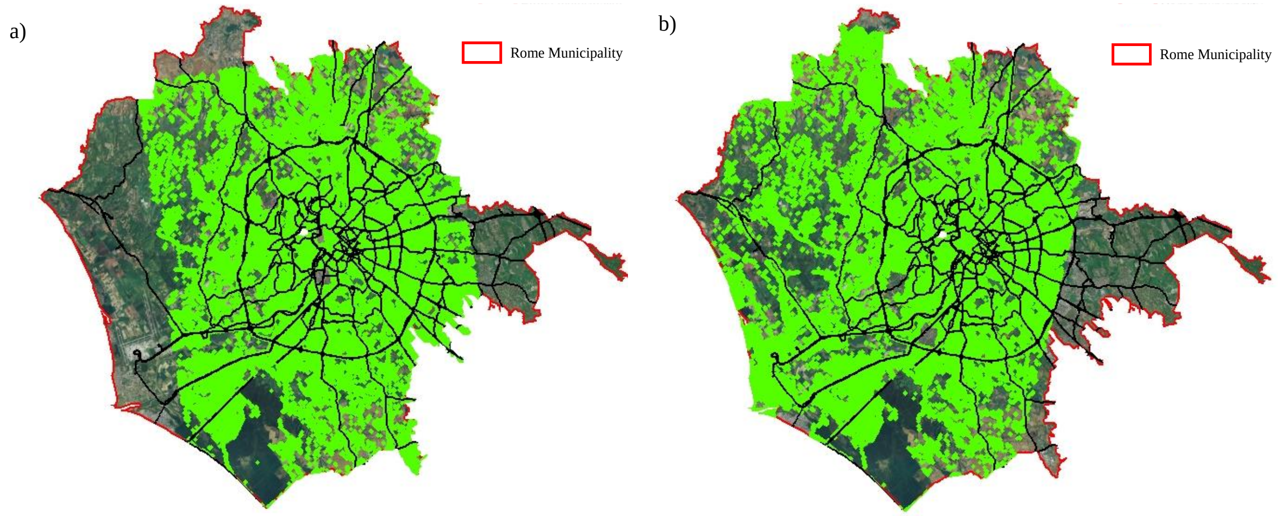

Figure 3. The monitoring points of the ascending (a) and the descending (b) orbit on the geographical area surrounding the infrastructure network subsystem.

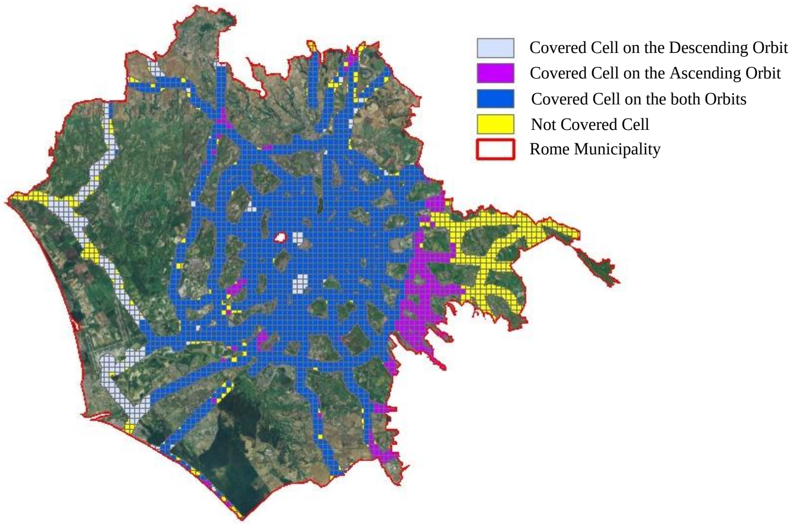

Figure 4. Cell coverage.

The average velocity (in space and time) value was then computed for each cell covered by both orbits, following Peduto et al. (2015). Once the average velocities for both ascending and descending covered cells were calculated, the procedure for the combination of the ascending and descending data made it possible to extract the Vertical (V) and East-West (EW) velocities and, consequently, the horizontal and vertical displacements (Figure 5) (Peduto et al. 2015). Figure 5 highlights the fact that both V and H displacements occurred in different elements of the infrastructure network subsystem.

These quantitative measurements enabled us to delineate the hazard.

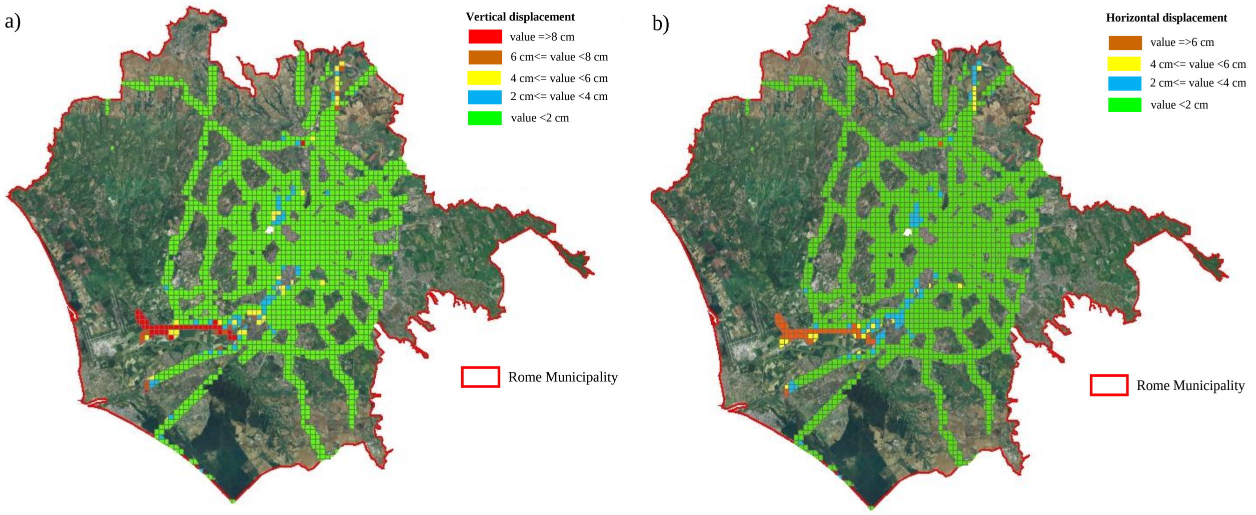

Figure 5. Vertical (a) and horizontal (b) displacements (in cm).

The V and H displacements were then processed in terms of V and H gradients in the GIS environment, and compared to the damage thresholds (Tables 1-2), expressing vulnerability, to identify the cells where damage occurred or is likely to occur within the infrastructure network subsystem. Note that the (vertical or horizontal) gradient is calculated as the difference between the (vertical or horizontal) displacements of two consecutive cells divided by the size of the cell. The risk maps expressed in terms of V and H gradients were then drawn, as shown in Figures 6(a) and 6(b), respectively.

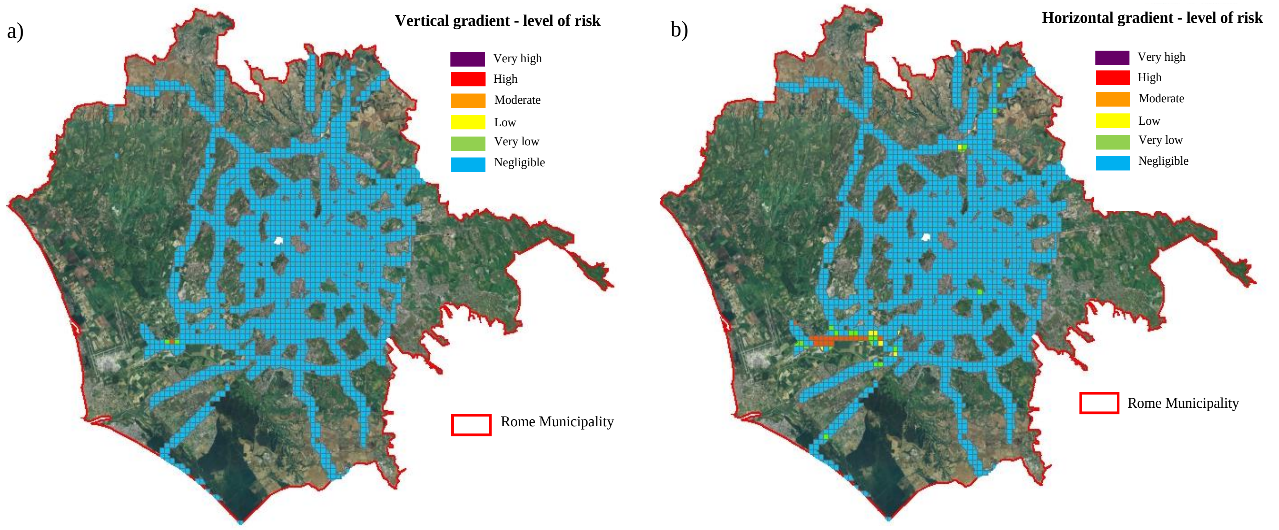

Figure 6. Risk maps of the infrastructure network subsystem in terms of vertical (a) and horizontal (b) gradients.

In the third phase, the risk maps deriving from the second phase were systemically analysed. In relation to the local risk maps (Figure 6), the overall subsystem considered was characterized by a common negligible risk in relation to both the V and H gradients. However, especially regarding the horizontal gradients (Figure 6(b)), one element managed by ANAS S.p.A. (Figure 2) was characterized by a moderate risk, whereas other connected elements, managed by ANAS S.p.A., the Province, the Municipality and Autostrade per l'Italia - ASPI (Figure 2), were characterized by a very low or low or moderate risk. This result may provide guidance for both organizational and governance modes, that could potentially be developed in two ways as follows.

First, the larger span of safety consists of most elements of the sub-system characterized by functional interdependency and negligible risk (Figures 2 and 6). As explained in Section 2, coordination between all the interested parts is to be preferred. Common functionalities among parts and a reasonable timeframe, in the presence of negligible common risk, facilitate joint management. In this way, the actors can adopt common rules and standard operating procedures. Specifically, coordination can result in the sharing of monitoring techniques with a sustainable cost/benefit ratio. These techniques give rise to lower costs than onsite sensors managed separately by local authorities and administrators. Arguably, satellite monitoring represents the most suitable jointly funded technical solution. There are also advantages in adopting common standards of prevention that have a similar environment and similar traffic characteristics.

Second, a separate span of safety consists of infrastructures characterized by moderate risk and the other connected infrastructures affected by very low or low risk (Figures 2 and 6), thus making a subset. In this case, as explained in Section 2, fragmentation from the sub-system is desirable: flexible management is to be preferred due to the different levels of risk. Focused interactions among the actors involved should depend on two factors relating to the different nature of the risk. There is a time dependency between the respective interventions as a result of the likely cascade effects due to functional interdependency. At the same time, there is a clear order in terms of the priority of interventions, with the infrastructures presenting the highest risk with the highest priority. Consequently, effective "loosely coupled" modes of governance represent a flexible mix of sharing and autonomy. Timeframes can be jointly determined, and as noted above, the cost of the monitoring techniques can be shared. In addition, different risk levels can be addressed autonomously with different procedures. For example, a mode of governance can be aimed at engineering interventions primarily to reduce the highest risk level. Subsequently, the following interventions need to be designed considering the subset of infrastructures with a view to reducing the lower risks simultaneously, avoiding cascade effects and obtaining advantages from economies of scale.

Finally, in line with the theoretical framework adopted, the analysis of the surrounding environment is an additional factor for the actors in terms of coordination and fragmentation. It extends the analysis from road infrastructures to the environment, and from the specific risk to the possible local causes of that risk.

The present study analysed the surrounding environment where the subsystem was highlighted by means of thematic maps relating to the landslide and flow hazard obtained from the *Geoportale Nazionale* (National Geological Survey) (Italian Ministry of the Environment: http://www.pcn.minambiente.it/viewer/) and illustrated in Figure 7. These two maps reveal a landslide and flow hazard close to the elements of the infrastructures affected by very low, low and moderate risk (i.e., the subset) (Figure 6).

Analysing the surrounding environment presents two main advantages. First, analysing provides an in-depth understanding of a risk that is present both within a subset and a system or subsystem. It takes into account a more comprehensive environment, rather than just a portion of the area, providing insight into its impact on infrastructure. Second, such analysis widens the span of safety by identifying additional actors who might be involved in risk management.

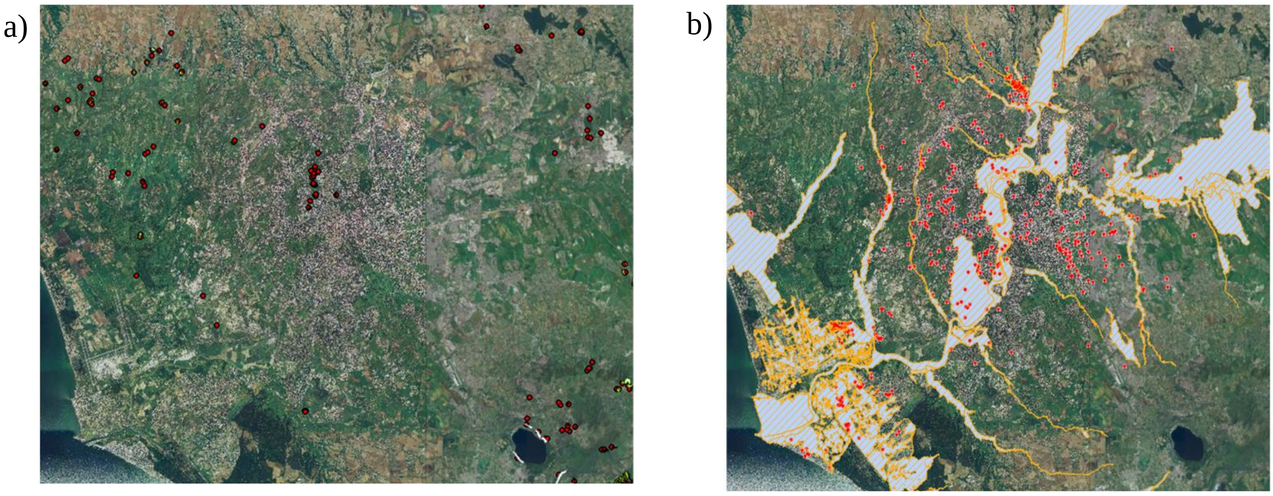

Figure 7. Other thematic hazard maps: landslides (IFFI 2007) (a) and flow (b).

The results of the study provide useful indications for designing local interventions in the interests of public safety. It could be useful to plan the use of the surrounding areas by means of engineering works (e.g., retaining walls, drainage systems) to protect the subset against landslides and excessive water flows. Essential information for the future development of road infrastructures can be provided to prioritize the locations characterized by a negligible, very low or low risk. In short, the proposed framework, together with an analysis of the surrounding environment, could support planning and strategies based on the idea that interaction between actors should not be considered to be predetermined but rather as necessary in certain conditions.

5. Conclusions

The risk management of infrastructures has traditionally been based on underlying models or theories focusing on isolated infrastructures and complex risk factors. This separation reflects the reality of the involvement of separate public/private authorities or administrators. However, recent studies have shown a growing interest in systemic analysis by leveraging the interdependency between infrastructures within a given system.

The present study offers new insights into the theoretical and methodological discussion about risk management concerning infrastructure at a given local level. By focusing on road infrastructures, the study proposed an interdisciplinary approach combining organizational studies and engineering. The study outlined a comprehensive framework that examines the interaction between parts achieved by means of two organizational modes: coordination and fragmentation. The need for coordination or fragmentation is determined by the complementary dimensions of the span of safety and the level of risk. The span of safety concerns the interdependency between infrastructures and the related actors. The level of risk above all determines the timeframe needed to address a safety issue and the priority of interventions adopted by the actors. Coordination and fragmentation can be achieved through specific modes of governance, which provide useful suggestions for collaborative interventions at a given local level. This theoretical framework was supported by the DInSAR technique that enables a system or subsystem to be monitored, consisting of the infrastructure at a local level. Its implementation is combined with the GIS technique. The study tested the sustainability of the proposed framework and the potential of the technique in Rome (Italy) and its surroundings. Within a general municipal system, the focus was on a subsystem mainly consisting of primary and secondary roads, administered by public and private actors. The study established that the overall subsystem of interest was characterized by negligible risk, thus requiring coordination since this level of risk can be handled with shared prevention procedures. At the same time, the study identified a separate span of safety, concerning an infrastructure characterized by moderate risk and other infrastructures, functionally connected, affected by very low or low or moderate risk, thus requiring fragmentation. In this case, the study outlined how effective “loosely coupled” modes of governance can be achieved through a flexible mix of sharing and autonomy. Moreover, the study provided useful indications in terms of planning specific interventions, such as protecting engineering works from landslides and excessive water flows. In addition, the results provided useful information for the future development of road infrastructures. In particular, they make it possible to identify the best locations characterized by a negligible, very low or low risk level.

The advantages and limitations of such an approach can be highlighted both in technical and conceptual terms. From a technical point of view, satellite monitoring covers a wide geographical area at a lower cost than traditional techniques. In addition, damage to the infrastructure does not result in the loss of the SAR sensors as in the case of traditional monitoring techniques. Two other advantages are first, time and site-dependent forecasting, and second, implementation of the data in a Building Information Model (BIM - DM560/2017) for the infrastructure network.

The technical limitations are as follows. First of all, the results always need to be validated, especially in the case of unacceptable risk (from moderate to very high risk) by means of in-situ or three-dimensional detailed analysis (at the structural level). This is due to the fact that the DInSAR data present a degree of uncertainty since they include scatterers that are not specific to the infrastructure network. Moreover, the effects of other human or natural hazards, with very high velocities (Arena 2014), cannot be monitored by the DInSAR sensors currently available. For these events, other strategies, types of prevention and monitoring data are required. All this additional information can be transposed into the GIS environment by means of thematic maps to define the level of risk.

With regard to the theoretical aspects, the main advantage of the present study is to provide conceptual and analytical tools for decision-makers to gain insight into the dynamics within a system and to avoid the risk of a lack of interaction among the actors and ineffective interventions. Given that previous studies have mainly addressed the needs and expectations of land-use planners, the present approach represents a significant step forward providing guidance for the local planning process.

The limitations of the theoretical aspects reflect the fact that they clash with the rigidity of the rules defining plans, strategies, and operational measures. Risk management often entails exclusive management. Furthermore, initiatives envisaging participation in planning often focus on public actors with a rigid definition of the respective interventions, that tend to be hierarchical. However, the present study underlines the need for modes of interaction that are both contingent on the context and non-hierarchical, since they are mainly based on the priority of intervention according to risk. Flexibility in addressing hazardous events can go hand-in-hand with effectiveness: in this sense, there is space for common adaptable interventions once an improved capacity to cope with unforeseen events has been achieved.

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