Road network management in the context of natural hazards: a decision-aiding process based on multi-criteria decision making methods and network structural properties analysis

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ABSTRACT: In mountain areas, transport infrastructures (roads, railways) are exposed to natural hazards such as avalanches, torrent floods and rockfalls. Road networks are known to be essential for economic, safety, social, environmental and safety reasons: they can therefore be considered as critical networks. Effects of natural phenomena on exposed roads can affect either users, road infrastructures or the linking function itself with indirect remote consequences. This paper describes a methodology based on structural properties analysis to assess the indirect vulnerability of road networks. Attractiveness factors (population flows, economic activities, access to rescue, health facilities . . . ) are used to identify the importance of road sections. Physical features (slope, width . . . ) and snow avalanches exposure, considering variable quality information, are used as constraints. The software GeoGraphLab (GGL) provides structural indicators which inform decision-maker about their networks criticality and resilience is used in the context of natural hazards.

KEYWORDS: snow avalanches, natural hazards, mountains, indirect vulnerability, roads, network structural properties, information quality

RESUME: En montagne, les infrastructures de transport (routes, voies ferrées) sont exposées aux phénomènes naturels tels que les avalanches, les crues torrentielles et les chutes de blocs. Les réseaux routiers sont reconnus comme essentiels pour des raisons économiques, sociales, sécuritaires et environnementales: ils font, à ce titre, ainsi partie des réseaux dits critiques. Les effets des phénomènes naturels sur les routes exposées affectent soit directement les utilisateurs, les infrastructures ou la fonction de liaison de la route avec des conséquences indirectes distantes. Cet article décrit une méthodologie basée sur l’analyse des propriétés structurelles des réseaux pour évaluer la vulnérabilité indirecte des réseaux routiers. Des facteurs d’attractivité (flux de population, activités économiques, accès aux services de secours, santé . . . ) sont utilisés pour identifier l’importance des sections de route. Les caractéristiques physiques (pente, largeur . . . ) et l’exposition aux avalanches, prenant en compte la qualité variable des informations, sont utilisées comme contraintes. Le logiciel GeoGraphLab (GGL) est mis en œuvre dans le contexte des risques naturels en montagne: il fournit des indicateurs structurels qui renseigne les décideurs sur la criticité et la résilience de leurs réseaux.

MOTS CLES: avalanches, risques naturels, montagne, vulnérabilité indirecte, routes, analyse des propriétés structurelles, qualité de l’information

1 INTRODUCTION

In mountain areas, roads and transport infrastructures are exposed to natural hazards such as avalanches, torrent floods and rockfalls. Road networks are essential for economic, social, envi-
Environmetal and safety reasons and can therefore be considered as critical networks (energy, transport, water supply, telecommunications) that can be ranged according to the consequences of their being disrupted (Figure 1) (Tacnet et al., 2012b).

This last case corresponds to indirect vulnerability relates to the consequences of road closures. Economic approaches, based on simple assumptions about road networks, have been proposed (Rheinberger et al., 2009). The criticality of closures depends on the importance of road sections which in turn is linked to the consequences of road closures and attractiveness factors of nodes which are connected through the network. Spatial analysis combined with graph theory have already been used for network analysis (Erath et al., 2009).

The analysis of network structural properties provide additional information about indirect vulnerability (Figure 4) due to networks disruptions (Gleyze, 2005). Most of natural risk assessments methods deal with direct vulnerability. The assessment of remote consequences of phenomena (corresponding to indirect vulnerability) remains indeed an important issue: the main goal is therefore to identify the importance, vulnerability and also the resilience of road sections in a context of natural hazards in mountains. The importance is related to the economic activities depending on what and where are the most critical sections.

The principle of structural properties analysis is to propose a diagnosis of the network including the assessment of road networks attractiveness: why do people have to use roads? How many use them? Which kind and amount of economic activities depend on road accessibility? What is the accessibility level to health, education, rescue equipments? How difficult and dangerous is it to use roads? Is there any possibility of diversion in case of road disruption?

The existing approaches based on network anal-
ysis do not propose both combinations of the- 
omatic factors (attractiveness and/or constraints) 
and structural properties indicators. This paper de-
cribes a new methodology to evaluate both 
the socio-economic attractiveness indicators and 
the importance of road networks sections exposed 
to natural risks management in mountains. This paper 
is organized as follows. Section 1 is a global intro-
duction that presents main risk features. Section 2 
presents backgrounds about multicriteria decision 
analysis and structural properties methodologies. 
Section 3 describes the developments which in-
clude successively, the adaptation of road network,
the calculation of attractiveness on nodes and con-
straints on edges of the networks and, finally, the 
structural properties indices. Section 4 is a discus-
sion of results and a conclusion stating the main 
perspectives.

2 BACKGROUNDS

2.1 Structural properties analysis

The structural network analysis allows for descrip-
tion of how far the network properties condition the 
accessibility from one point to another. The central-
ity indicator measures the level up to which a road 
is used to reach any point (importance factor). The 
average (mean) distance indicator shows how easy 
or difficult it is to reach a point on the network. This 
distance may be different from a classical euclid-
ian distance (in meters) since it corresponds to an 
accessibility factor.

GeoGraphLab (GGL) software implements a 
methodology based on the structural properties 
of networks Gleyze (2005) Mermet (2011) dedi-
cated to the exploration of any infrastructure net-
work (transport, energy, telecommunications . . .).

Structural approach involves different complexi-
ties nature. A combinatorial problem is first encoun-
tered, since the size of an OD space is computed 
in $n^2$ (where $n$ is the number of nodes). Therefore, 
the more nodes the network contains, the more the 
storage of shortest paths (Figure 5) is important 
in terms of memory. These storage problems in-
volve a second complexity : computation time of 
implemented computation algorithms, e.g. all Pairs 
shortest Paths algorithm in $O(n^2)$ (Chan, 2007), 
betweenness centrality (Parlebas, 1972) (Freeman, 
1977) and average distance (Pitts, 1979) in $O(n^2)$ 
). These technical problems of storage and algorithm-
raise a last complexity: what is the best display 
to exploit results and how to highlight important in-
formation in the best way? Indeed, it is not easy 
to sort among all the resulting data. Consequently, 
it is difficult for a user who wants to understand the 
relational potentiality of a transportation network, to 
correctly analyze and to interpret the results.

GGL offers a friendly interface to model network 
and to calculate the structural indicators which pro-
vide useful information to decision-makers depend-
ing on their activity (users, network managers, land-
use managers) and the scale of analysis (local, 
regional, national). In comparison with classical 
network analysis software as proposed in existing 
G.I.S. such as ArcGIS, GGL is original and new be-
cause of 1) specially designed for structural anal-
ysis of networks, 2) a large collection of indicators 
to be computed, 3) possibility to combine indica-
tors in a graphical language, 4) multi-scale repre-
sentation by aggregation of network’s components.
Recent developments consist in importation of thematic data and coupling of multicriteria decision analysis methods in order to evaluate both attractiveness and constraints respectively on nodes and edges of network (Figure 15).

Among all the proposed and possible indicators, two are commonly used. First, the betweenness centrality measure equals to the number of shortest paths from all nodes to all others that pass through that node. It represents the load of network components by all the shortest paths. Figure 6 shows this measure computed in GGL. It is usually used to identify edges and nodes which are strongly requested (i.e. important for displacements) for shortest paths travels. The darker is the color of network objects, the more important are these components to travel on the network. Betweenness centrality can help to highlight highly stressed components placed on so-called sensitive areas (bridge, one-way road ...). Secondly, the average distance corresponds to an accessibility measure. For all nodes, shortest paths are computed to all others. The value of the average distance for a node is the mean of all these paths to all others. Figure 7 shows this measure computed by GGL. Light (dark) colors on components show the more (less) accessible areas of the network according to its structural aspect.

Figure 6: Betweenness centrality.

Figure 7: Mean Distance.

2.2 Multicriteria Decision Making in a context of imperfect information

The Multicriteria Decision Making (MCDM) methods (Figueira et al., 2005; Tacnet, 2009, 2012) aim to choose, sort, and rank alternatives and solutions according to predefined criteria in the decision-making process. MCDM consists in identifying decision purposes, defining criteria, determining preferences between criteria, evaluating alternatives and solutions and analyzing sensitivity with regard to weights and thresholds. The (Analytic Hierarchy Process) AHP is a MCDM method whose principle is to arrange the factors considered to be important for a decision in a hierarchic structure descending from an overall goal to criteria, subcriteria, and finally alternatives at successive levels. It is based on three fundamental steps: breaking the problem down into its components, comparative assessments and hierarchic structure or synthesis of priorities. As a single synthesizing criterion approach, the analytic hierarchy process (AHP) (Saaty, 1980) is a special case of a complete aggregation method based on an additive preference aggregation. Despite some well known drawbacks (Ishizaka and Labib, 2009), this method remains simple to implement and explain. Many others MCDM methods exist including some recent ones proposed to consider information imperfection (Tacnet and Dezert, 2011, 2012; Dezert and Tacnet, 2012).

3 METHODOLOGY

Based on structural networks analysis, the proposed approach aims first to assess the accessibility level of mountain territories and, secondly, to identify critical roads sections depending both on their exposure to phenomena and also on the importance of roads in an economic, social and environmental context. The first step of the methodology characterizes the initial state of socioeconomic factors across the territories using thematic databases to produce attractiveness factors. The second steps translates them into structural indicators (linked to importance) of each road sections using both network structural properties and constraints derived from a multi-criteria analysis of natural hazards.
3.1 Network description

The analysis of network is done at different scales ranging from local (community) to regional scale. We analyze whether each road is important and accessible because of physical factors such as width, altitude, sinuosity and finally vulnerable to closures due to natural hazards. A key issue concerns the assessment of possible diversion which determines the resilience of the network.

Three different scales (regional, departmental and local approach) require an adaptation of resolution and type of roads considered. This step is both important and time-consuming (about 3 weeks of work for network pre-processing) in the whole process. The initial network from BD Topo (Figure 8) has to be simplified for GeoGraphLab simulations. We finally use BDRoute500 to describe the network (Figure 9) because it fits correctly to network analysis even if it does not contain information related to physical constraints such as slopes used in our approach. A specific development is required to mix those data sources.

3.2 Attractiveness indices

The application corresponds to the Provence-Alpes-Côte d’Azur (PACA) Region in the south-east of FRANCE (valley, department, region) (Figure 10). Economic data coming from INSEE databases are analysed in order to identify and locate main activities. These data are used afterwards in order to determine attractiveness indexes (Figure 11).
3.3 Natural hazards constraints

Data about snow avalanches result from the French Localization Map of Avalanche Phenomena (called CLP A in French, see [www.avalanches.fr](http://www.avalanches.fr)) which provides information about maximal phenomena extensions (Bonnefoy et al., 2010). As it records past events, it is used to inform and educate people about the existing areas in mountainous regions, where avalanches actually occurred. In our context, we present a new development related to information quality description and use. The CLP A records the widest limits of both either observed or historical avalanche events and past avalanches whose marks remain still visible in the field (mainly on vegetation). The extensions of these observed avalanche phenomena are therefore based on oral or written eye witness accounts about events and their consequences and/or on the analysis of aerial photographs supplemented by field analysis. Information quality (certainty level) is clearly described with a difference between proven and assumed information (Figure 12).

CLP A has recently been updated in order to allow spatial analysis based on avalanches limits: lines, corresponding to successive inputs, have been transformed into polygons. From now, it is therefore possible to spatially combine the extents with other objects corresponding to housing, networks .... However, the link between information quality and decision is well known (Tacnet, 2009; Tacnet et al., 2012a; Dubois and Prade, 2006) but the analysis of the influence of information quality on risk management decisions remains an emerging approach (Tacnet, 2009). On the basis of CLPA, two values of exposition are calculated (Figure 14), the lower corresponds to proven exposed road and the higher corresponding to possible exposition. Those values are then used as constraints in the structural properties analysis. Figure 13 presents an extract of spatial information about snow avalanches (CLPA), including its the quality level and the coding rules, which are used to analyze the proven and assumed road exposure. Such information can be used in advanced spatial information fusion methodologies recently proposed and still under progress (Tacnet et al., 2010).
3.4 Criteria aggregation and structural properties analysis

Two main structural properties indicators \textit{betweenness centrality} and \textit{remoteness} are calculated at a regional scale (Figure 16). They are based on attractiveness on nodes (population flow considering in- and out-coming population (Figure 11), economic activities, access to health, rescue, safety services, education...) and constraints on edges (physical properties, natural hazards exposure, snow avalanches, rockfalls, torrent floods...). The AHP methodology is used to aggregate indirect vulnerability criteria. The results are obtained for the road network for each domain of activity. The GGL software allows to introduce several thematic layers and to combine them in order to produce structural properties analysis in a direct or indirect way (Figure 15). Those results provide information on critical sections for decision-making according either to users, road managers or land-use planners requirements and objectives.

4 DISCUSSION - CONCLUSION

This paper describe an innovative methodologies related to risk assessment focusing on the specific case of roads exposed to natural hazards. Multicriteria decision analysis methodology and structural properties analysis allow to identify the most important and critical road sections according to economic, social or human factors and then estimate the indirect vulnerability, accessibility and resilience of a network.

This approach improves and extends previous developments (Tacnet et al., 2012b): first, the software GGL has been improved to consider thematic layers and integrate multicriteria analysis in a graphic user interface. Secondly, methodologies of economic attractiveness assessment have been improved and formalized. Finally, both new features of CLPA database and information quality (resulting from the use of the French Snow Avalanche database) can influence the results of assessment.

From a technical point of view, the pre-processing steps (attractiveness indicators, network description) are very time-consuming. The methodology can obviously be applied to other exposed networks and/or other kinds of natural hazards (developments for rockfalls, torrent floods are under progress...). The development of GGL is still going on with a special focus on improvement of its friendly-user interface. From a scientific point of view, the future works will concern the integration of decision support methods, spatial information representation and information imperfection representation: the objective is to provide effective information for risk management decisions but also to make decision makers aware of the reality and influence of information imperfection on their decisions.

Acknowledgments

These developments are funded by the French Ministry of Ecology, Sustainable Development and Energy (MEDDE), in charge of risk prevention and Irstea through its internal program PITI for new technologies development (standing for Pre-incubation Transfer Innovation).
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