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Feasibility study of a loss-driven earthquake early warning and rapid response systems for tunnels of the Italian high-speed railway network

S. Fabozzi*, E. Bilotta, M. Picozzi, A. Zollo

University of Naples Federico II, Italy

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A B S T R A C T

Linear infrastructures have strategic importance and impact on the social and economic conditions of many countries, hence the seismic risk management of existing and new designed ones is a crucial issue in earthquake-prone areas. High-speed and high capacity railways are an example of infrastructures that assume increasing importance in developed countries, since they permit rapid transit of people and freight.

Due to the seismicity of the country, the case of the high-speed railways Italian network appears suitable for assessing the feasibility of a loss-driven earthquake early-warning system based on the real-time estimation of the expected damage probability and lead-time. Among the several subsystems that compose the network, the paper focuses on tunnels, since they are largely present along the route of the existing high-speed lines and of the new ones currently under design.

This work describes a procedure that exploits the disaggregation of the seismic hazard to define sets of virtual seismic sources potentially affecting railway's tunnels. Hence, the probability of seismic damage to tunnel structures and the time available for implementing real-time mitigation procedures can be calculated. Such a procedure is applied to two tunnels of the high-speed system with different structural layout. The procedure suggests that for the considered tunnels the best option for undertaking seismic risk mitigation measures would be an on-site threshold–based early-warning system. However, the foreseen probability of structural damage to the tunnel lining is low in both cases.

The proposed methodology can be easily generalized to different targets to design the optimal configuration of an earthquake early warning system, and applied to control, manage and maintain the tunnel structures along the high-speed railway network.

1. Introduction

Over the last decades, many countries faced an increasingly growing demand of urbanization and were thus forced to exploit the underground space in order to develop their 'physical inter-connectivity'. A well-fitting example of physic inter-connectivity among urban areas is the high-speed rail network (defined according with the more recent technical specification of the European Committee as the rail network where trains travel at a speed $V_{HS} \geq 250$ km/h, hereinafter HSR), which widely spreads in many parts of the world with hundreds of kilometers underground.

Nowadays, high-speed rail systems cover a large slice of the mass transportation in the world, shortening distances and reducing travelling time. Such advantages have, definitely, an important economic impact on many countries that continue to invest in this sector, but also social benefits within a highly globalized context.

The HSR system has achieved the higher performance in Japan, where the Tokaido Shinkansen has been the first high speed line in the world, followed by Europe and America respectively. The European HSR system developed later than the Japanese one, but nowadays it counts the 60% of the worldwide network, with the ambitious goal, still under completion, to connect the entire continent by the Trans-European Networks – Transport (TEN-T). Italy is fully integrated in the TEN-T, both in terms of achieved effective velocity (i.e., 300 km/h) and of national rail network coverage (i.e., about equal to 8%; Table 1).

Considering that Italy is a highly seismic country, the effects of ground shaking induced by earthquakes on the HSR systems are a matter of concern for the maintenance of existing railways and the design of the new ones. Undoubtedly, the major concern for the railways companies is the potential derailment of a high-speed train due to ground shaking, since it would cause severe injuries, casualties and economic loss. However, damages induced by an earthquake to the railway infrastructure (i.e. embankments, bridges, tunnels) are also important considering the direct economic losses produced by the

* Corresponding author.

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Table 1
Worldwide High Speed rail classification (extrapolated from https://www.goeuro.it/treni/alta-velocita).

Country -	Record velocity Km/h	Effective velocity Km/h	Network coverage %	Population coverage %
1 *Japan* SC Maglev	603	320	12.23	36.55
2 *France* TGV	575	320	6.79	12.69
3 *China* Shanghai Maglev	501	350	29.22	10.70
4 *Corea* KTX	421	300	1.62	44.67
5 *Spain* AVE	404	320	20.05	20.51
6 *Italy* Frecciarossa 1000	400	300	7.91	18.47
7 *Germany* ICE	368	320	4.75	18.28

service disruption and any possible indirect effect (such as train derailment).

Focusing on the effect of ground shaking on tunnels, that are largely present along the route of the Italian high-speed railways network, this work describes the seismic hazard and the seismic vulnerability of the tunnel lining. This work is motivated by the observation that the high-speed rail network crosses complex seismogenic regions with a moderate to high seismic hazard (Fig. 1), and therefore, tunnels of the railways network might undergo important level of acceleration, and accordingly damages.

Among the various aspects that can be considered during a performance analysis of a tunnel (i.e. structure; geological, geotechnical and hydrological uncertainties; localized phenomena), the seismic vulnerability is certainly one of the most important in areas exposed to high seismic hazard. Past earthquakes, indeed, revealed that important seismic events can damage the tunnel structure and limit or temporarily inhibit its functionality [1–5]. The available data are mostly referred to tunnels excavated with traditional methods. These studies show how the deformation induced by the earthquake to the tunnel can produce different crack patterns in the lining (in longitudinal, transverse or generally inclined direction) according with the complex seismic soil-tunnel interaction mechanism, which in turn depends on the lining and soil stiffness properties, the soil-structure interface behaviour, the maximum soil acceleration and the direction of propagation of the seismic event with respect to the structure.

From an engineering point of view, the seismic risk management of tunnels is accomplished by computing the probability of damage (P_f) due to seismic actions. This is calculated as the convolution of the seismic vulnerability (V) and the seismic hazard of the specific site (H). Furthermore, the whole seismic risk assessment must include also the exposure of the tunnel itself, as well as that of the high-speed trains and their customers, that is variable with time.

A widespread methodology for seismic vulnerability assessment for single structures or a class of them makes use of fragility curves computed for increasing seismic hazard level. The combination of fragility curves and seismic hazard derived scenarios can then be used to study the tunnel performance under seismic actions, also in real-time [6].

Taking in to account the importance of developing strategies suitable for the real-time mitigation of seismic risk for railways tunnels in

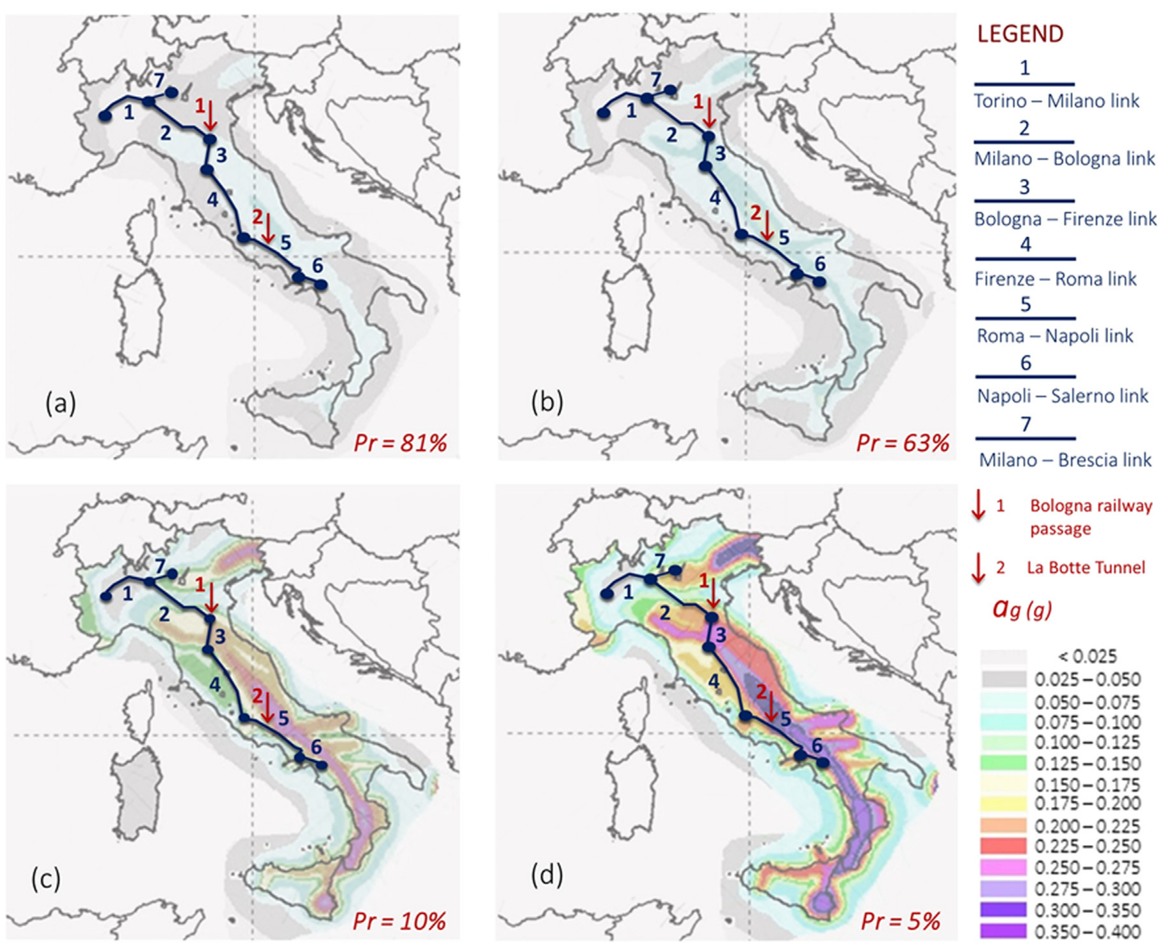

Fig. 1. Italian high speed rail system (operational) combined with the hazard maps for a probability of exceedance, PR, equal to (a) 81% (return period TR = 30 y), (b) 63% (return period TR = 50 y), (c) 10% (return period TR = 475 y), and (d) 5% (return period TR = 975 y). (Hazard maps extracted from INGV, http://zonesismiche.mi.ingv.it).