# Seismic damage and implied traffic delay assessment for a highway bridge of Egnatia Odos Greece

**Akrivi Chatzidaki** – Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, Athens, Greece, e-mail: cakrivi@central.ntua.gr

**Angeliki Gerontati** – Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, Athens, Greece, e-mail: agerontati@mail.ntua.gr

**Dimitrios Vamvatsikos** – Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, Athens, Greece, e-mail: divamva@central.ntua.gr

**Abstract:** The seismic damage and the implied traffic delays are assessed for two structurally independent twin bridges, one per travel direction, which form the G7 bridge of the Egnatia highway in Greece. They are reinforced concrete structures with a monolithic pier-to-deck connection that were built using the cantilever method of construction. To enhance the seismic assessment resolution, a component-based approach is followed that allows evaluating damage scenarios for individual critical bridge components and propagating them to assess the performance of the entire system. This necessitates linking the component damages to the actions that the road operator would take in order effect repairs, i.e., by reducing the speed limit in any of the lanes and/or closing any of them until repairs are finished. These interventions typically lead to traffic delays for the entire highway that are computed on an event basis via event-based probabilistic seismic hazard analysis by considering the component-to-asset and asset-to-system interdependencies. The aim is to develop a decision support tool for pre-event risk assessment and rapid post-event inspection of critical road infrastructure by combining hazard, vulnerability and sensor information to predict the resulting consequences both on the asset and the system level at every step during an asset's recovery back to full functionality.

**Keywords:** road infrastructure, seismic risk assessment, bridges, traffic delays

## 1. Introduction

One of the greatest challenges that road operators are facing nowadays is the safe operation of road infrastructure (RI) networks as well as their fast and efficient inspection and recovery after catastrophic events. To this scope, considerable effort has been made for assessing the impact of any damaging event both on an asset-level, i.e., for the critical RI assets such as bridges and tunnels, as well as for the entire highway network, either focusing only the seismic hazard (Kilanitis and Sextos 2019; Pitilakis et al. 2014) or by considering multiple hazards (Argyroudis et al. 2020). Many researchers have focused on quantifying the impact of any damaging event on the highway, either in terms of loss of connectivity on one or more highway segments (Kang et al. 2008), or in terms of traffic delays and associated increases in travel time, as for instance by considering changes in the traffic flow capacity, disruption of specific routes of the network etc. (Costa et al. 2018; Miller 2014). Still, it remains a challenge to apply a practical multi-hazard approach on realistic infrastructure that allows assessing the follow-up to a failure in terms of traffic delays at every step of a system's recovery back to full functionality.

In response, the PANOPTIS project integrates multi-hazard resilience assessment of highway assets with real-time sensor information to provide a holistic decision support tool for pre-event assessment and rapid post-event inspection of critical road infrastructure under multiple hazards. It helps road operators efficiently inspect, maintain and safely operate existing road networks and mitigate the risks. PANOPTIS focuses on multiple hazard and damage/consequence scenarios that allow accommodating rapid damage and consequence identification. To this scope, an enhanced resolution is adopted for the highway assets, allowing tracing back potential consequences to individual components with more ease, in order to facilitate the rapid inspection after a potentially damaging natural hazard event. The asset-level consequences are propagated to the entire system in order to assess the implied traffic delays after an event by considering the asset-to-system interdependencies. Herein, the framework for assessing the seismic damage is presented using the G7 bridge of the Egnatia Odos highway in Greece as the case study, while the implied traffic delays are computed by only considering the Metsovo-Panagia segment of the highway.

## 2. Framework for quantifying traffic delays

In case of any catastrophic event, the Road Operator (RO) might need to close a number of lanes and/or reduce the speed limit in the remaining open ones until inspection and repair actions are completed. These measures can either be employed locally, i.e., by restricting traffic before and after the damaged asset (e.g. bridge) or globally, i.e., along an extended segment of the highway. In both cases, this results in increased travel times and decreased highway traffic capacity. In PANOPTIS, the travel time and traffic capacity are assessed before and after the occurrence of a potentially damaging event, as well as at every time instance along the recovery process back to full functionality. To achieve this, the component/asset/system interdependencies are considered in all aspects of impact assessment, propagating said relationships to response, damage, direct and indirect losses, as well as the recovery process, naturally leading to the level of the entire system.

Starting from individual assets, the baseline treatment of FEMA P-58 (2012) is employed; it utilizes component-based fragility curves, which provide the probability of a component violating the limit state of interest given its Engineering Demand Parameter (EDP), in order to assess damages on a local basis. The fragility curves are convolved with the damage-to-consequence/loss functions associated with each component. In our case, the consequences are quantified in terms of speed limit and/or number of lanes closed, as well as time needed for repair actions to be completed. The consequences effected by all asset components are combined together, summing up losses and downtimes, or choosing the worst-case traffic restrictions, to determine the recovery on an asset basis. The recovery status of all assets is merged over the entire highway to assess the implied traffic delays for the system.

The traffic delays are assessed for the Metsovo-Panagia segment following a simplified approach, as its limited length of 16km, low number of interchanges in between and absence of alternative routes within the segment allows obtaining a good estimate of the traffic delays without employing more complex tools. Specifically, if the traffic demand is considerably lower than the capacity, any potential reduction of the speed limit in one or more lanes will only cause minimal delays, associated with the reduced speed limit itself. Still, if the reduced capacity falls close or under the traffic demand, significant delays should be expected, requiring additional time for each vehicle to traverse the highway. The delay per vehicle is affected by the ratio of the time that a vehicle needs to traverse the highway while driving under the original speed to the new time the vehicle needs, while additional delays due to queueing are approximated by employing the control delay of a vehicle approaching an unsignalized intersection (TRB 2000).

In our case, in order to simplify the illustrated example, it is assumed that the G7 bridge is the only earthquake-damageable asset within the Metsovo-Panagia segment. Thus, depending on the reductions of the speed limit and lane closures that are implied by any repair actions on the G7 bridge, the traffic delays for the entire highway are determined. In case of any repair action that would require closing the highway, the vehicles are assumed to travel via the alternative road shown in Fig. 1. Still, this is an old road of poor maintenance, thus there is a great chance to be damaged even in less severe earthquakes than the ones that would cause significant damages on the G7 bridge. Herein, we assuming that the alternative route stays mostly intact, while moderate-to-heavy traffic would result to about 1.3hrs of travel time.


Fig. 1 – Metsovo-Panagia segment of the Egnatia highway in Greece showing also the alternative road.

## 3. Case-study bridge

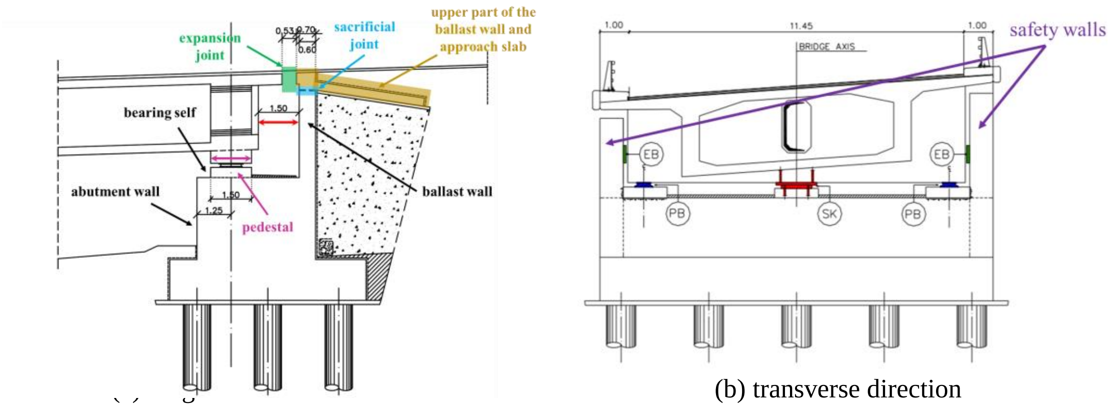
The G7 bridge (Fig. 2) consists of two structurally independent twin bridges with each of them carrying one traffic direction of two lanes. They were built following the cantilever method of construction with in-situ concreting. Both of them have three spans with a total length of 270m with their longitudinal axis being curved in both horizontal and vertical plane. The deck is a prestressed single-cell concrete box girder with varying depth and is monolithically connected to the two piers. The piers are founded within the rock via concrete shafts while the deck is supported via two pot-bearings at each abutment that allow the horizontal deck movements in both longitudinal and transverse directions while a third bearing is added in the middle, having a transverse shear key that restricts transverse displacement until a maximum shear force of 2500kN is reached.

During a seismic event, the bridge may displace longitudinally, transversally or even vertically. Due to monolithic pier-to-deck connection, such displacements become of importance at the abutments at which the deck is connected via bearings. Understanding the bridge behaviour in all possible directions is of significant importance in order to identify its critical components that might sustain damage during earthquakes and whose performance defines the damage states. For the G7 bridge, the piers, bearings, abutments, ballast walls, pedestals, deck and the expansion joints are considered as the critical bridge components (Fig. 3, Chatzidaki et al., 2020). These are modelled in detail and their response is monitored during the analysis in order to allow assessing their potential damage and then propagate it to the entire system.

(a) location of the bridge (adapted from Google Earth)

(b) G7 bridge

Fig. 2 – G7 bridge of the Egnatia Odos highway in Greece.



(b) transverse direction

Fig. 3 – Critical bridge components of deck support at the abutment (adopted from Chatzidaki et al. 2020 and Giannelos and Vamvatsikos 2011).

## 4. Assessing the seismic response of the bridge

The nonlinear model of the bridge was developed by Vamvatsikos and Sigalas (2005) via the OpenSees platform (Mazzoni et al., 2000), as shown in Fig. 4. To assess its structural response, the model is subjected to Multi-Stripe Analysis using sets of ground motion records that are selected to be consistent to the site-specific hazard based on the Conditional Spectrum (Lin et al., 2013, Kohrangi et al. 2017). The state-of-the-art average spectral acceleration, *AvgSa*, (Cordova et al., 2001, Kazantzi and Vamvatsikos, 2015) is adopted as the Intensity Measure (IM):

$$AvgSa(T_{Ri}) = \left( \prod_{i=1}^{n} Sa(T_{Ri}) \right)^{1/n} \tag{1}$$

It is the geometric mean of $n$ spectral acceleration ordinates, $Sa$, at periods $T_{Ri}$. Each $Sa$ ordinate is the geometric mean of the 5%-damped spectral acceleration from the two horizontal components of each ground motion. The periods, $T_{Ri}$, in our case are equally spaced in [0.3s, 3.0s] with an increment of 0.1s. During the analysis, the response of all critical bridge components is monitored via properly selected Engineering Demand

Parameters (EDPs) that can adequately characterize their response. For instance, the drift is selected for monitoring the response of the piers while the maximum deck-to-abutment gap closure is employed for the expansion joint and the ballast wall.

The response of all bridge components is discretized into limit states, which for the pier are defined based on the closed-form equations of Stefanidou (2015), while for the rest of the components they are derived based on manufacturer data as well as discussions with professional bridge engineers. The consequences associated with each component and limit state in terms of speed limit and repair time are determined based on the standard operating procedures of the highway operator.

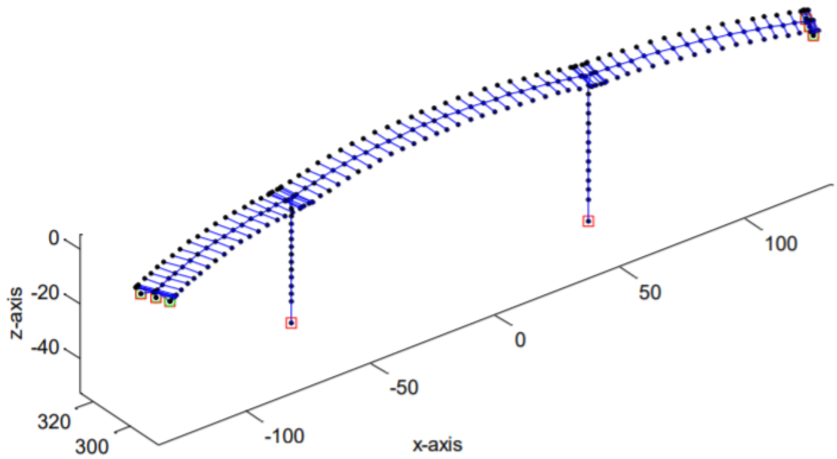



Fig. 4 – Three-dimensional model of the G7 bridge (adopted Vamvatsikos and Sigalas, 2005).

## 5. Seismic damage and traffic delay assessment

### 5.1. Scenario-based traffic delays

The traffic delays are firstly computed for an arbitrary seismic event that is randomly selected from the stochastic event sets of thousands of event realizations that represent the site-specific seismicity. The stochastic event sets are determined via Event-Based Probabilistic Seismic Hazard Analysis (PSHA, Cornell 1968, Weatherill et al. 2015). To this scope, the opensource OpenQuake software (Monelli et al., 2012) is employed using the area source model of SHARE (Giardini et al., 2013) and the ground motion prediction equation proposed by Boore and Atkinson (Boore and Atkinson, 2008). The *AvgSa* is adopted as the IM for the hazard assessment to ensure consistency with the structural analysis. The selected IM field is shown in Fig. 5 whose magnitude is $M = 6.1$ and *AvgSa* at the location of the G7 bridge is 0.26g. For the given event, multiple realizations may be generated by randomly sampling the damage and consequence distributions. In our case, for an arbitrary selected realization, damage is caused in both expansion joints while the rest of the bridge components do not sustain considerable damage. In order to repair the damage, the RO needs to reduce the speed limit to 60km/h in one lane per direction, while closing the second. By alternating the closed and the open lane, repairs can be effected across the entire width of the highway without shutting it down. These interventions are expected to last 3 days assuming that both expansion joints (one at each abutment) are repaired in parallel.

If this happens in a day with light traffic, i.e., when traffic demand is significantly lower than the traffic capacity, the traffic delays are expected to be minimal since all vehicles will travel via the open lane without this resulting in queues. Essentially $D < C$, $t_0$ = 16km / 90km/hr, and $t_1$ = 16km / 60km/hr, leading to a delay of $t_1 - t_0 \sim 0.09$hrs. Still, if the event happens in a day of heavy traffic when many people use the highway, then considerable traffic delays are expected.

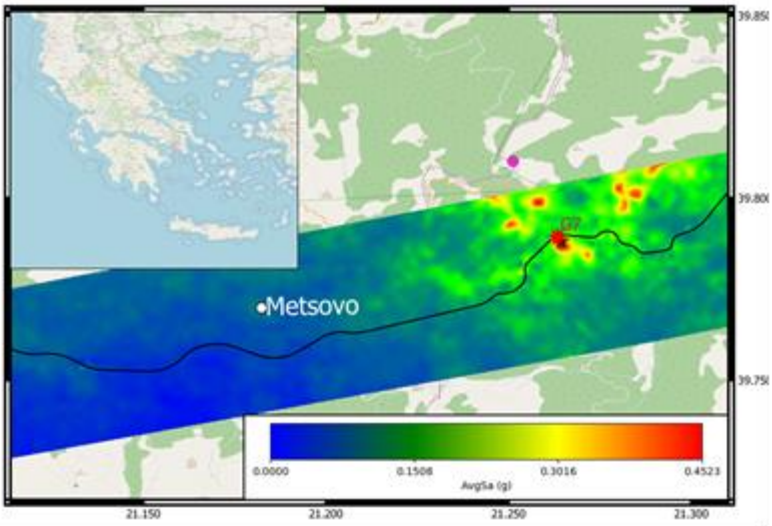



Fig. 5 – Seismic intensity measure field showing the highway by the continuous black line, the location of the G7 bridge in red and the epicenter of the earthquake in magenta.

## 4. Conclusions

A methodology is presented for assessing the seismic response and the implied traffic delays for the highway due to a potentially catastrophic event. This approach can be applied for assessing damages on individual highway/road infrastructure assets while the combined results can be used for the assessing the traffic delays for the entire interconnected system. The framework is quite straightforward, still the toughest part is the definition of the limit states and associated consequences on a component basis in a consistent way for all components. This challenge requires the assistance of engineers specialized in the design and construction of similar structures as well as of road operators experienced in road maintenance, repair and rehabilitation actions. Once the damage states and consequences are defined, the implied traffic delays can be easily quantified.

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