2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

DECISION SUPPORT FOR ROAD INFRASTRUCTURE RESILIENCE: THE PANOPTIS PERSPECTIVE

Dimitrios VAMVATSIKOS[1]

Abstract: *The PANOPTIS consortium aims to leverage existing tools and services as well as remote sensing technologies to deliver an integrated platform that can address road infrastructure (RI) multi-hazard resilience. The scope of the project incorporates RI structural components (bridges, overpasses, interchanges, tunnels, slopes, retaining walls, pavements, and surface water drains), non-structural components (tunnel ventilation systems, traffic cameras and signposts), as well as interconnected non-RI components, such as power transmission lines and telecommunication towers. Both detailed and surrogate structural models will be developed for RI and non-RI components, quantifying and incorporating the epistemic uncertainty due to the detailed models' reduction to surrogacy to allow a rapid high-resolution assessment of vulnerability, whereby loss, functionality and downtime become directly tied to rehabilitation/emergency action planning. The focus is on the development of a rapid-response decision-support tool that will employ measured data immediately after any seismic event to issue inspection prioritization protocols, facilitate the rapid assessment of the state of the RI, and help increase its resilience to catastrophic events.*

Introduction

One of the greatest challenges facing transport operators and engineers is the fast and efficient inspection, assessment, maintenance and safe operation of existing road infrastructure (RI) networks. This is even more important in seismic areas, where earthquakes meet aggravating factors such as ageing, extreme weather conditions, landslides, increased traffic demands, changes in use, inadequate maintenance and deferred repairs. In its entirety, this encompasses the challenge of resilience assessment, as well as resilience safe-guarding and improvement for entire highway networks. Either when considering multiple hazards (Gidaris et al. 2017) or when focusing only on the seismic hazard (Kilanitis and Sextos 2019), this remains a challenging problem that requires considerable effort and resources to resolve at the scale of a national or transnational highway. In view of this challenge, the PANOPTIS project was conceived to leverage the power of sensor information with advanced computational methodologies into tackling the assessment and improvement of resilience for highway infrastructure in Europe. In the following, the framework developed by the PANOPTIS consortium will be presented and its salient characteristics with regard to seismic risk and resilience assessment will be discussed.

The PANOPTIS Concept

The PANOPTIS system will be based on the input of two types of sensors, namely (I) sensors that provide information on the seismic hazard (e.g., seismographs), and (II) sensors that provide information on a structure (e.g., accelerometers attached to a bridge). Each type serves a different role, as it offers information on the input to the structural models (loads) or directly on their response (displacements, accelerations).

Three modes of operation are envisioned with respect to the occurrence of a seismic event. On the pre-event operation, only type II sensors may be usable within the framework of health monitoring to help us assess the condition of the RI elements. In this phase, risk assessment of the entire RI network is performed and "all" possible scenarios are calculated and their consequences in terms of damage and recovery ae assessed. In essence, this is a time-consuming all-encompassing operation that employs the best currently-available data to arrive at a set of different potential future outcomes. Re-assessment is only required if something changes in the elements monitored, e.g., due to deterioration, repairs, replacement etc.

[1] Assistant Professor, National Technical University of Athens, Athens, Greece, divamva@mail.ntua.gr

In the trans-event phase, where the event has just happened (or is presently unfolding) some limited information, especially from type I sensors, will be available. Seismographs tend to be reliable sensors that can offer direct estimates of seismic intensity, especially after automating the signal processing (e.g., baseline correction and filtering). Several type II sensors, especially strain gauges and accelerometers, may similarly offer directly information, but others are often less reliable, either because they are not available on time (e.g., an unmanned aerial vehicle that needs to get on station for transmitting information), or because their information on structural response cannot be verified a priori and needs some careful calibration and/or interpretation before being used to derive conclusions. Either way, limited sensor information will be directly available and it will be employed mainly to prune the set of potential scenarios into a more manageable size of the most probable outcomes that can guide the operators' actions in the first few critical moments. This is by nature a rapid near-real-time process, rather than a full-fledged assessment of what happened.

In the post-event phase of operation, the operators have the luxury to collect and assess data from field inspection and all available sensors. This can be employed to update the relevant RI element fragility/vulnerability functions and continuously reassess the multitude of scenarios as the RI condition evolves in its recovery path following rehabilitation actions. After the recovery is completed, the clock is reset, and we have entered our new pre-event phase.

Pilot studies and assets considered

To test this framework in practice, two pilot studies have been envisioned in co-operation with Egnatia Odos SA and Acciona SA. Egnatia Odos has offered a segment of the homonymous highway connecting Thessaloniki with Metsovo, in the moderately seismic mountainous spine of Greece. It comprises long bridges, tunnels and steep slopes in a high-altitude environment. Acciona has offered a segment of the Madrid to Barcelona highway, crossing plains and hills along the low-seismicity Spanish landscape.

Both networks contain a wealth of assets, including

1. RI geo-structural assets: Bridges, toll booths, signposts, engineered and non-engineered slopes, overpasses, intersections, road tunnels, drainage shafts, drainage tunnels, RI control building, etc.
2. RI non-structural components: Cameras, sensors, tunnel ventilation, fire-fighting equipment, control room components, etc.
3. Adjacent non-RI components that influence the RI functionality: Mainly telecommunication towers, and overhead power transmission lines.

The vulnerability and recovery of each asset needs to be assessed and incorporated into the all-encompassing interconnected highway model, that takes sensor information and hazard input feeds and estimates damage and loss.

Modeling of assets

Two tiers of assets are envisioned. Tier II assets are generic RI or non-RI elements that will be modelled by generic fragility and vulnerability "class" functions (Porter et al. 2014). Thus, only a few archetypes will be modelled in some detail and assessed in each case. Examples include all non-RI components, and all RI non-structural components, plus the signposts, some typical intersections, drainage shafts, repeated overpasses etc. Tier I assets are influential RI elements that require structure-specific treatment. For these, both detailed and reduced-order models will be created to offer a comprehensive understanding of their response. In general, detailed models are good for considering issues of corrosion, localized damage, and thus correlating with sensor information. They are not very useful for propagating uncertainty and performing seismic assessment due to their considerable computational expense. Thus, simpler models with a low number of degrees of freedom will be employed to conduct all dynamic analyses.

As an example, Figure 1 shows the plan and longitudinal section of the G7 bridge of Egnatia Odos. Bridge G7 is circular in plan with a 320m radius and comprises a three span 75+120+75m continuous deck monolithically connected to piers and simply supported at the abutments (Figure 1). The prestressed concrete deck structure is a single cell box girder with depths varying from 7.25m at the piers to 2.75m towards the mid span and abutments. The box type piers M1 and M2 have outer dimensions 7.35 x 4.0m, 0.75m wall thickness and clear heights of 41.70m and 49.50m respectively. Both piers are founded on cylindrical 10m-diameter 15.0m-long solid rockshafts bearing on rock. Solid seat type abutments founded on bored piles are provided at both ends (Figure 2). Free-sliding pot bearings and a shear key are installed at the abutment support axis to restrict the deck movement in the radial direction. A pair of seismic stoppers at each abutment achieves restriction of the radial movements in case of excessive earthquake forces that cause yielding of the shear key.

A commercial finite element program was employed to model the bridge in detail, incorporating tendon prestressing information and careful modeling of section stresses during the multiple phases of the balanced cantilever construction. Instead, the opensource OpenSees platform (McKenna et al. 2000) was selected to form the reduced-order model. Pier columns were modeled using a flexibility-based fiber element formulation with an exact corotational formulation to account for geometric nonlinearities (P-Δ effects). The deck was assumed to remain elastic and was represented with centerline beam-column elements that were appropriately selected to simulate the gradual changing of the cross-section (Figure 3). The foundations, being embedded solidly in rock, were assumed to be fixed. Finally, the abutment pot-bearings were simulated with complex multi-linear springs that include the gap between the deck and the abutment walls and the breaking of the shear key.

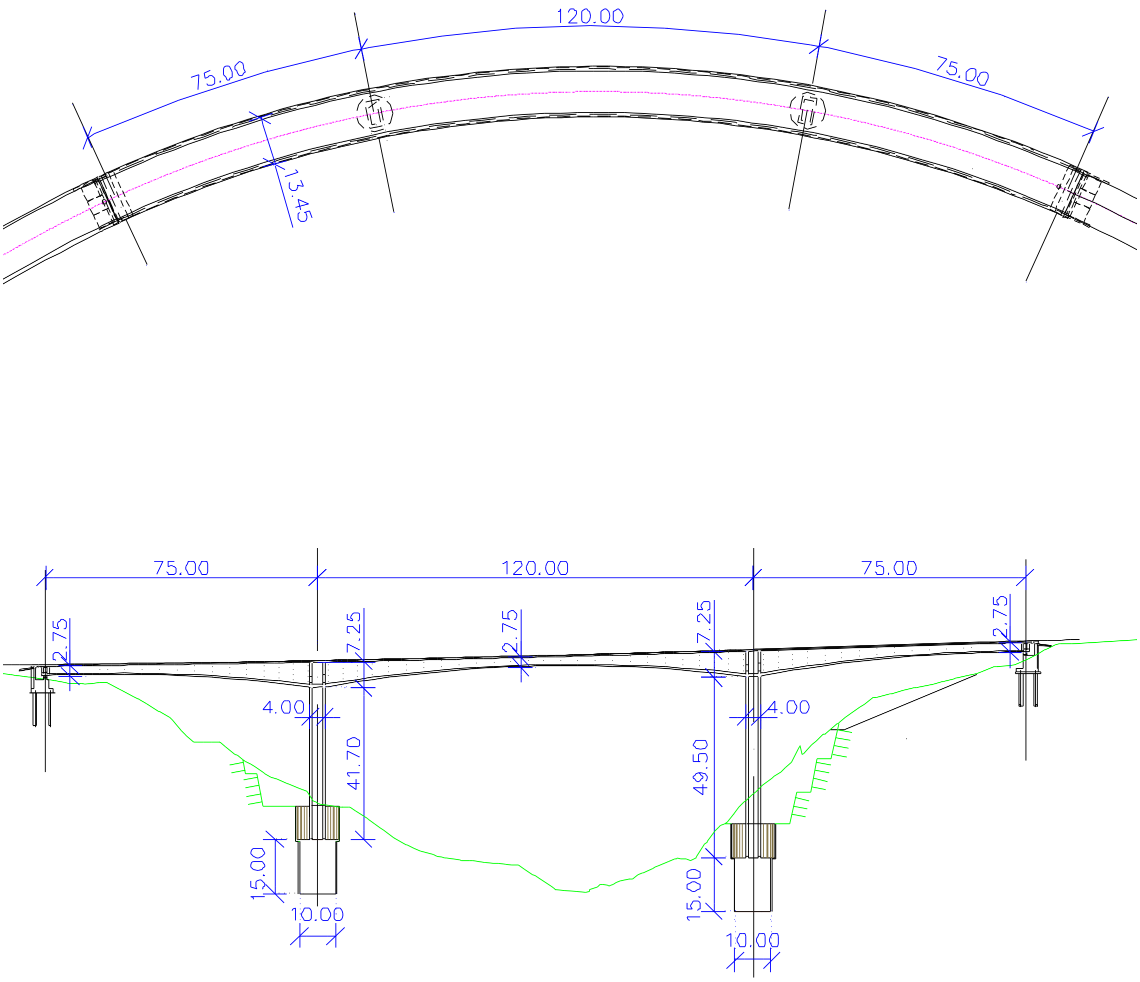

Figure 1. Plan (top) and longitudinal (bottom) section of the G7 bridge, Egnatia Odos, Metsovo (dimensions in meters).

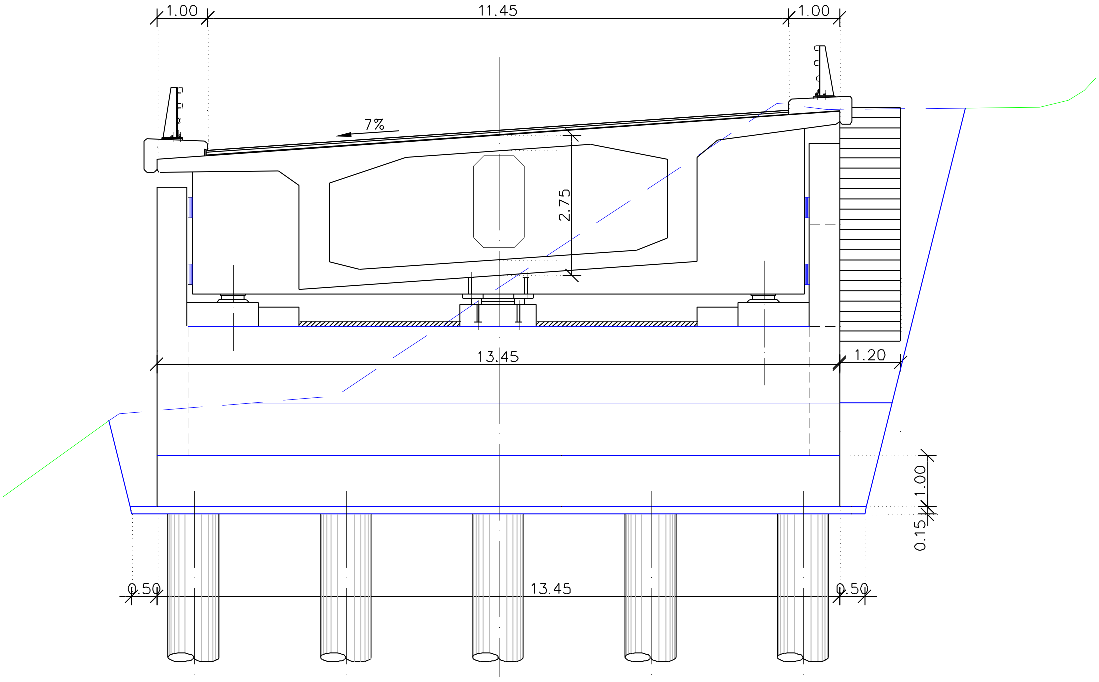

Figure 2: Abutment – bridge connection details (dimensions in meters).

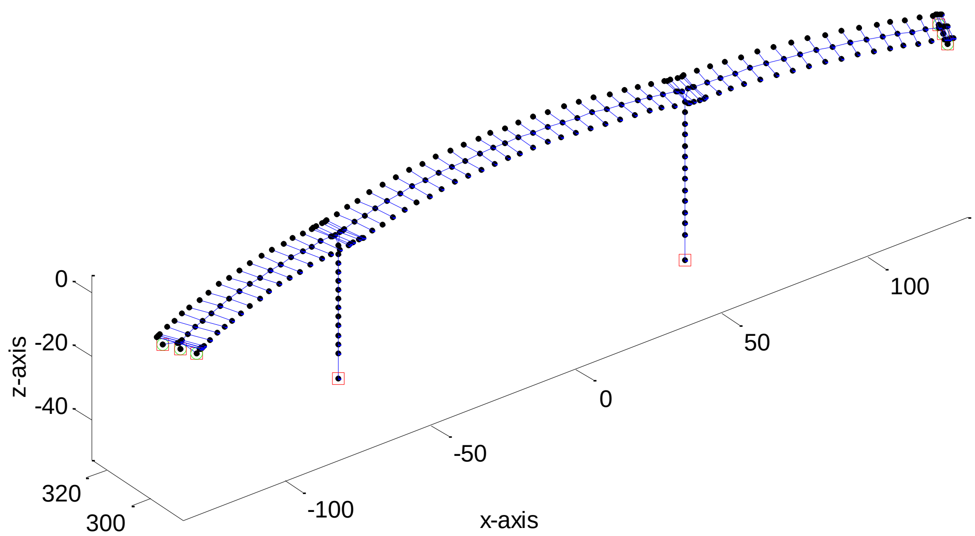

Figure 3. Opensees reduced-order model of the G7 bridge, Egnatia Odos, Metsovo (dimensions in meters). Dummy nodes and elements have been added left and right of the centreline deck elements to visualize the deck width.

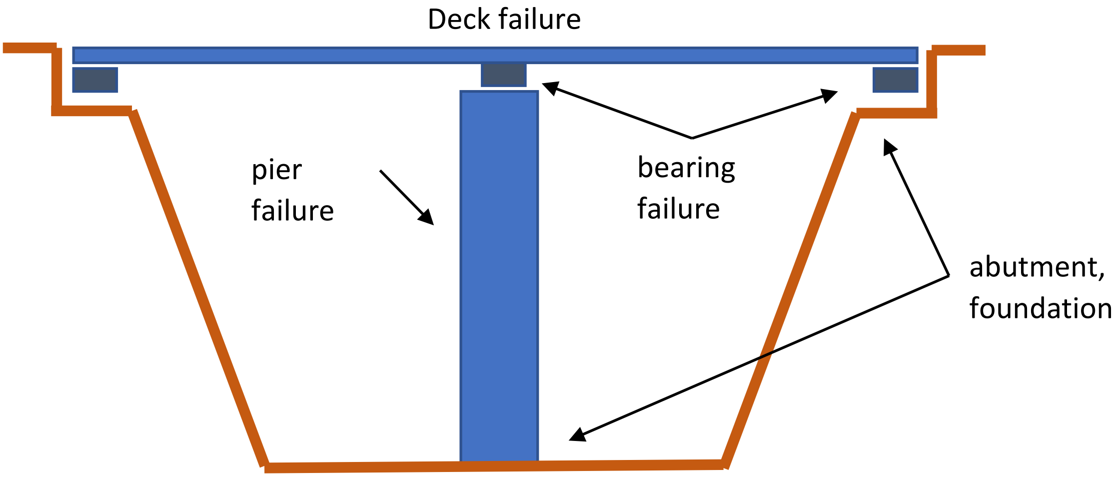

Figure 4. Conceptual breakdown of bridge to components and associated fragilities

Assessment Approach

In the assessment of Tier II structures, classical fragilities will be employed. These are essentially probability-valued functions of the intensity measure of choice (e.g., the peak ground acceleration) that can define the damage state of an entire structure, but not of its individual components. For the less important Tier II cases this constraint is not an issue, but for the more influential Tier I cases, as in the conceptualized bridge of Figure 4, this becomes a problem. Such fragilities cannot differentiate between damage received by different components. Thus a global rating of “moderate damage” that may have been triggered cannot be reliably traced back to individual bridge parts, which for the same level of damage incur considerably different repair times and costs. For example, given that no deck unseating has occurred, bearing damage is probably the easiest to repair; such bearings are typically designed to be replaceable anyway.

To achieve such a granularity in our assessment, we follow the idea of the FEMA P-58 approach to use component fragilities, i.e., functions of probability of damaging a single component given the EDP and convolve with the losses/consequences implied by each component. This will generate vulnerability functions, which are specific to the individual asset and will help delineate the resulting consequences with more ease. While component fragilities have appeared frequently in the literature, even for bridges (Padgett et al. 2010), they are typically aggregated to a global system fragility for cost assessment, rather than maintaining the separation of the different components for cost assessment.

While the estimation of direct repair costs is fairly straightforward, the estimation of indirect losses due to business interruption is not. Since our target in PANOPTIS is the RI operator, rather than the community, region or state that it serves, the indirect losses will be tied to the annualized reduction of traffic handling capacity due to seismic events, and the associated loss of toll fees that are the primary source of income for the user. Such losses shall be tracked throughout the recovery phase of the RI network to full, pre-event functionality.

To better estimate loss of tolls to moderate and low intensity events, the fragility of many ancillary RI and non-RI assets comes into play. Excessive slope displacements, even minor debris, fallen trees, ventilation equipment or signage bridges, will typically close one or more lanes, forcing costly diversions and repair operations. It is expected that several such minor infrastructure failures of neglected elements may rival the cost of the failures of well-maintained bridges or tunnels when aggregated over many events in the lifetime of the highway.

To achieve this level of detail, event-based probabilistic seismic hazard analysis will be employed, to determine “all” potential seismic scenarios that may happen in the RI area. An aggregation of these results at the 10% in 50yrs level appears in Figure 5 for Egnatia Odos. This may increase considerably the cost of simulation, yet this is only a pre-event phase issue, where computational time is not at a premium. On the other hand, it will offer the needed detailed picture of “all” events that can happen, together with damage and cost predictions, growing a large tree of potential events that can later be pruned in the trans-event operation phase to help PANOPTIS achieve its goal of sensor-driven near-real-time assessment.

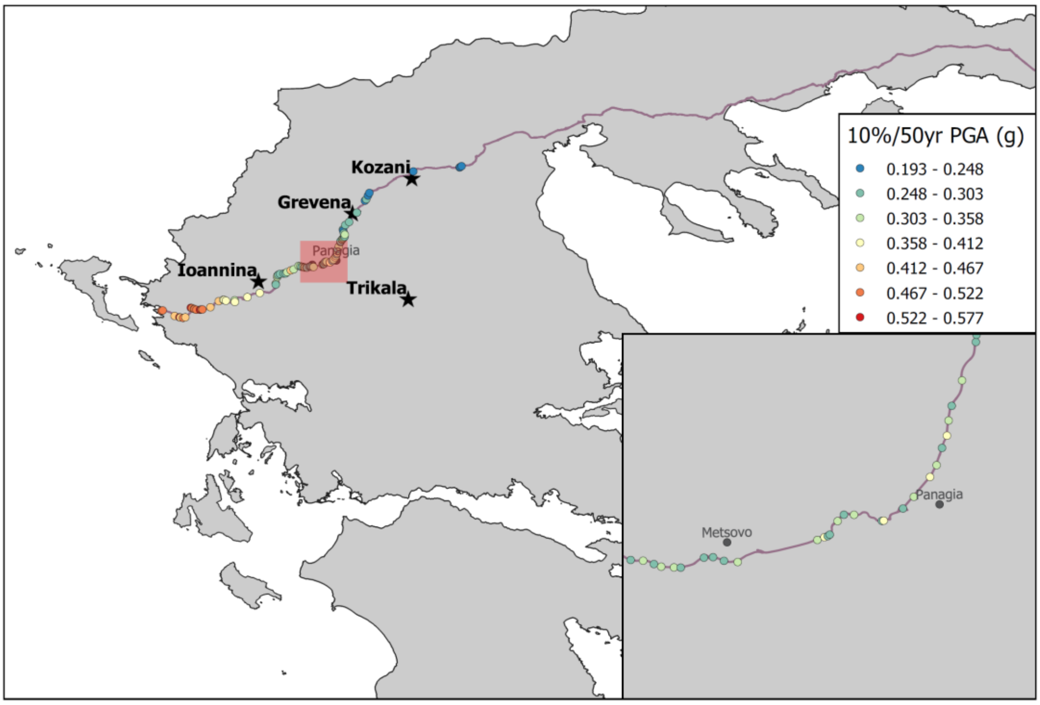

Figure 5. Spatial nature of seismic hazard along a continuous part of the Egnatia Odos highway: 10% in 50yrs PGA values according to the SHARE model (Giardini et al. 2013). The insert figure in the bottom right shows the area of interest for the pilot study (Metsovo-Panagia).

Acknowledgements

Financial support has been provided by the Innovation and Networks Executive Agency (INEA) under the powers delegated by the European Commission through the Horizon 2020 program "PANOPTIS-development of a decision support system for increasing the resilience of transportation infrastructure based on combined use of terrestrial and airborne sensors and advanced modelling tools", Grant Agreement number 769129.

References

FEMA P58-1. Seismic performance assessment of buildings: 1–Methodology. Prepared by the Applied Technology Council for the Federal Emergency Management Agency. 2012.

Giardini D, Wössner J, and Danciu L (2014), Mapping Europe's Seismic Hazard, *Eos, Transactions American Geophysical Union*, 95(29): 261–262.

Gidaris I, Padgett JE, Barbosa AR, Chen S, Cox D, Webb B, Cerato A (2017), Multiple-hazard fragility and restoration models of highway bridges for regional risk and resilience assessment in the United States: State-of-the-art review, *Journal of Structural Engineering*, 143(3):04016188.

Kilanitis I, Sextos A (2019). Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas, *Bulletin of Earthquake Engineering*, 17(1):181-210.

McKenna F, Fenves GL., Jeremic B and Scott MH (2000), Open system for earthquake engineering simulation. Available at: http://opensees.berkeley.edu (Accessed 30/05/2019).

Padgett JE, Dennemann K and Ghosh J (2010), Risk-based seismic life-cycle cost–benefit (LCC-B) analysis for bridge retrofit assessment. *Structural Safety*, 32(3):165-173.

Porter K, Farokhnia K, Vamvatsikos D and Cho IH (2014), Guidelines for component-based analytical vulnerability assessment of buildings and nonstructural elements, *GEM Technical Report 2014-13*, Global Earthquake Model Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2014.13.