

Seismic resilience assessment of critical infrastructures – Case study of M1 highway bridges

László Gergely Vigh^{1,*}, Dániel Honfi², László Dunai¹, Ádám Zsarnóczy¹,
József Simon¹, Máté Dohány³, Zsolt Berki³

¹Budapest University of Technology and Economics, Department of Structural Engineering, Budapest, Hungary

²RISE Research Institutes of Sweden, Gothenburg, Sweden and Ramboll, Copenhagen, Denmark

³FŐMTERV Civil Engineering Design Pte. Ltd., Budapest, Hungary

Received: 19 November 2021; Accepted: 19 January 2022

Summary

Safety and security of critical infrastructure networks is one of today's top priorities, as they are getting increasingly complex and interdependent. Thus, their potential failure due to unforeseen and extreme events may result in excessive direct and indirect losses. Recently, focus has shifted from protection to resilience, i.e. the ability of a system exposed to a hazard not only to resist, but accommodate to and recover from the hazard effects.

This paper – by the implementation of the IMPROVER technological resilience analysis – demonstrates the seismic technological resilience assessment of a section of M1 Highway in Hungary. Resilience against the community's tolerances as well as risk-based resilience indicators are evaluated. The results suggest that technological resilience could be improved, thus certain resilience treatment options are highlighted.

Keywords: critical infrastructure, resilience assessment, technological resilience, seismic hazard

Kritikus infrastruktúrák szeizmikus ellenálló képesség vizsgálata – Az M1 autópálya hidak esettanulmánya

Vigh László Gergely^{1,*}, Honfi Dániel², Dunai László¹, Zsarnóczy Ádám¹,
Simon József¹, Dohány Máté³, Berki Zsolt³

¹Budapesti Műszaki és Gazdaságtudományi Egyetem, Hidak és Szerkezetek Tanszék, Budapest, Magyarország

²RISE Research Institutes of Sweden, Gothenburg, Svédország és Ramboll, Koppenhága, Dánia

³FŐMTERV Zrt., Budapest, Magyarország

Összefoglalás

A kritikus infrastruktúra-hálózatok biztonsága napjaink egyik legfontosabb prioritása, mivel ezek egyre összetettebbek és kölcsönösen függenek egymástól. Így az előre nem látható és szélsőséges események miatti esetleges meghibásodásuk túlzott mértékű közvetlen és közvetett veszteséget eredményezhet. A közelmúltban a hangsúly a védelemről a rezilienciára, rugalmasságra helyeződött át, vagyis a veszélynek kitett rendszer azon képességére, hogy nemcsak ellenálljon, hanem alkalmazkodjon is a veszélyhatásokhoz, és helyreálljon azokból.

Jelen cikk – az IMPROVER technológiai ellenállóképesség-elemzés felhasználásával – az M1-es autópálya egy szakaszának szeizmikus technológiai ellenálló képességének vizsgálatát mutatja be. Az értékelés az IMPROVER keretein belül kifejlesztett, az ISO 31000 kockázatkezelési folyamatába integrálódó ICI-REF keretrendszer (IMPROVER Critical Infrastructure Framework) követi. A keretrendszer különféle módszereket ajánl a kritikus infrastruktúra ellenálló képességének felmérésére.

Elsőként meghatározzuk és számszerűsítjük a vizsgált szakasz szeizmikus veszélyeztetettségét a valószínűségi szeizmikus veszélyeztetettség analízis segítségével, melynek eredményeképpen a helyszíneknek a spektrális gyorsulás – túllépési valószínűség kapcsolatát mutató veszélyeztetettség görbéit kapjuk meg. Ezt követően különböző károsodási szintekhez meghatározzuk az érintett hídszerkezetek sérülékenységi görbéit, mely a spektrális gyorsuláshoz tartozó

tönkremeneteli valószínűséget mutatja. Az esemény és a károsodás bekövetkezése esetén megváltozó útpálya kapacitás és forgalmi helyzet alapján az áteresztő képesség csökkenése mellett a menetidőtöbblet is számítható, így a közvetlen károk költségei mellett az indirekt költségek is számszerűsíthetők, és így a bekövetkezési valószínűségekből és a költségekből a kockázatot számítjuk.

Értékeljük a közösség toleranciáival szembeni rezilienciát, valamint a kockázatalapú reziliencia mutatókat. Részletes leírást adunk a forgalomsszimulációkat is magában foglaló katasztrófaelhárítási és helyreállítási modellek alkalmazásáról. A cél az, hogy kiszámítsuk a várható felhasználói késések időbeli alakulását a különböző elemzett forgatókönyveknél, és összegezzük az ebből eredő várható költségeket a végső helyreállításig. A reziliencia értékelése két megközelítésen alapul: 1) összehasonlítás a felhasználói toleranciával, és 2) a reziliencia kockázatalapú értékelése. Az eredmények alapján a technológiai reziliencia javítható, melyre több kezelési lehetőséget is felvázolunk. Az autópálya komplex reziliencia-kezelési stratégiáinak kidolgozásakor azonban az IMPROVER-en belül kifejlesztett egyéb módszerek, például a szervezetelemzés (IORA) és a holisztikus önértékelési (CIRI) eszközök eredményeire is támaszkodni szükséges.

Kulcsszavak: kritikus infrastruktúra, rezilienciavizsgálat, technológiai reziliencia, szeizmikus veszély

Introduction

Critical infrastructure

As the critical infrastructure (CI) networks are becoming increasingly complex and interconnected, they might become more vulnerable to the effects of potential devastating natural and man-made hazards, which may result in significant direct and indirect consequences.

Which of the infrastructures shall be considered as critical infrastructure? These typically include the highway network, telecommunications networks, public utilities, and many other infrastructures that provide fundamental services for the society.

The *European Council Directive (2008)* provides the following definition of critical infrastructure: “An asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions.”

The above example well illustrates that it is difficult to give an exact and objective definition of critical infrastructures, that is uniformly agreed across Europe. Hungarian law also addresses critical infrastructures, refer to Act 2012/CLXVI, Act 2011/CXXVIII, Government Decrees 65/2013. (8/3), 161/2019 (4/7), 249/2017 (5/9), 234/2011 (10/11), 1249/2010 (19/11). The law requires risk assessment and management for critical infrastructures. The law also defines certain infrastructures as critical infrastructure, e.g. Danube bridges are included. By the application of risk analysis, the importance and criticality of an infrastructure and the risk of extreme events can be quantified.

CI protection (CIP) and national risk assessment in Hungary

In 2007 a Green Paper about the Hungarian program on CI protection was published which defines 10 critical infrastructure sectors, namely: energy, ICT, transporta-

tion, water, food, health care, finance, industry, administration (law and government), public safety/security and defense.

The 2080/2008 (30/6) Government Decree about the CIP National Program defines a common framework for CIP, initiates sector-based consultations; sets up the regulatory concept; establishes links to Critical Infrastructure Warning Information Network *CIWIN* (2013); and approves the Green Paper. In 2008 and 2009 sector specific consultations and surveys took place, continued with regional consultations and seminars in 2010.

The 1249/2010 (19/11) Government Decision (in response to 2008/114/EC identification and designation of European critical infrastructures (ECI) and the assessment of the need to improve their protection) states that there is no ECI in Hungary. The document further concerns with the CIP Working Group, coordination and contact, national CI designations, reporting to EC, and consultation forums.

In 2011 a new legislation in the field of disaster management was implemented in Hungary. The Belügyminisztérium Országos Katasztrófavédelmi Főigazgatóság (National Directorate General for Disaster Management – <https://www.katasztrofavedelem.hu/>) became the main authority for the 1) identification of potential critical infrastructure elements, 2) keeping CI under official supervision, and 3) arrangements, institutional system, identification and selection process of CI. National Directorate General for Disaster Management is responsible for organizing prevention, preparedness and protection of CI in the case of natural and man-made disasters.

In 2012 a new legislation about CI identification, designation and protection is proposed which defines and categorizes CIs, defines operator's obligations, sets criteria for providing information, defines authorities, regulates functioning, describes registration, defines deadlines and responsibilities, describes design lifetimes and inspections and outlines connection to EU. The definition of CI sectors was slightly changed and included 11 sectors: energy, ICT, transportation, water, agriculture,

health care, social security, finance, law and government, public safety and security, and defense. At the time of writing the paper sector specific legislation was implemented in all sectors except transportation, below which the current case study falls.

A pilot initiative for the National Risk Assessment in Hungary was prepared in 2011 (Gyenes 2011). This served as a basis for a so called “ex-ante” (before the event) report detailing the common methodological framework for national risk assessment to be completed. This was considered necessary, since the risk assessment practices and methodologies in various sectors and disciplines differ. The proposed risk assessment methodology contains three main steps:

1. identification of hazards and risks,
2. performing the risk analysis, and
3. evaluation of risks and analysis of capabilities.

The report discusses climate change adaptation aspects, covers critical infrastructure protection, follows a multi-hazard risks approach, and it is consistent with relevant EU policies and uses ISO 31010 terminologies.

The approach is based on defining risk scenarios impacting various risk areas. The scenarios are to be prepared for two time periods: 5 and 25 years. The possible impacts are divided in various categories such as: 1) fatalities (including premature death), 2) injuries and illness, 3) sustained natural and environmental damage, 4) financial and material losses, 5) social unrest, 6) disturbances in everyday life, 7) weakening of governmental institutions at national level, and 8) weakening of governmental institutions at regional level.

Concerning CI, the impacts on different critical infrastructure sectors are described as criteria for evaluation. For transportation the assigned criterion is “disturbances in everyday life”. It should be mentioned, however, that for the complete evaluation of a scenario, the weighted average of various criteria (impacting various sectors) need to be considered.

The report discusses a possible simplified, risk matrix-based method where classification is based on the intensity and duration of impact (damage consequences in terms of people affected) as Table 1 illustrates. For the evaluation of the impacts value matrices are used. The impact criteria are classified as: A – low consequences, B – significant consequences, C – sever consequences,

D – very severe consequences, and E – catastrophic consequences.

The evaluation matrix for the criterion “disturbances in everyday life”, which is suggested to be used for critical transport infrastructure, is given in Table 1. The evaluation is based on the duration of the impact and the number of people affected.

Resilience

Safeguarding critical infrastructure is essential in order to support the functioning of society by mitigating risks and reducing them to acceptable levels. However, CI cannot be protected by all means as the costs of protective measures might outweigh the potential benefits.

Protection in general includes all activities aimed at ensuring the functionality, continuity and integrity of critical infrastructures in order to deter, mitigate and neutralise a threat, risk or vulnerability. However, protection typically focuses on improving of the resistance of the infrastructure against various hazard scenarios. Thus, proper design shall be accomplished by providing sufficient safety margin against future extreme events. Therefore, protection is rather a passive measure for safety provision. Furthermore, design for protection is complicated by the fact that besides foreseen extreme events, unforeseen scenarios might unfold as well.

In the previous years a shift has been observed from CI protection to enhancing infrastructure resilience. A suitable general definition as per UNISDR (2009) is as follows: “The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.” The definition well reflects that much emphasis is put on restoration, meaning how (by what actions, how quickly, at what cost) to recover and maintain the functionality of the infrastructure after an extreme event.

When assessing resilience, aspects of the different actors shall be considered and analysed in an integrated way. The following major resilience domains are typically addressed (Tierney–Bruneau 2007):

- societal: reflects local community’s problems; in the case of CI, e.g. transportation access, delays, communication capacity, etc.;
- organisational: business continuity, e.g. operation of CI, maintain or quickly regain function;
- technological: resistance, robustness and restoration capacity;
- economical.

One way to quantify resilience is to introduce resilience indicators (Pursiainen et al. 2016). There are various concepts and options, the selection among which is strongly dependent on the investigated problem and the focus, especially in terms of resilience domain in focus. The actual problem should always be deeply studied in

Table 1 | Risk matrix-based classification of infrastructures

Duration	Number of people affected			
	<10 000	<100 000	<1 000 000	1 000 000<
1–2 days	A	A	B	C
3–7 days	A	B	C	D
1 week – 1 month	B	C	D	E
More than 1 month	C	D	E	E

Source: Gyenes, 2011

order to find and understand the most relevant indicators. Resilience indicators are often based on performance or function loss and recovery functions. As for a highway network, the road traffic capacity, travel time between two points (or increased travel time or travel delay), etc. can be selected as the performance indicator. Risk-based resilience assessment prefers the latter one, as the economic loss caused by the extra travel time can be monetized. The change in performance over time is reflected by the so-called resilience triangle (time function of performance) (Bruneau *et al.* 2003), as shown in Figure 1. Performance level of normal operation (Q_0) suddenly decreases in the event of an incident (e.g. certain traffic lanes are closed after an accident, thus reducing traffic capacity and increasing travel time). Thereafter, via the recovery interventions, performance is gradually restored to the level of normal functionality. Technological resilience can be characterized by generating this function and calculating the area shaded in the figure. Smaller area means higher resilience (full functionality is restored in shorter time). On these bases, by assigning probability of occurrence of the event and the cost of consequences, the risk-based resilience assessment is established.

A further alternative to the resilience evaluation is to compare the resilience triangle with the so-called toler-

ance triangle (Honfi *et al.* 2018; Petersen *et al.* 2019). The tolerance triangle reflects how much performance loss can be tolerated over time (e.g. how much travel delay is tolerated by the highway user). In such a case the area where the calculated performance loss and recovery function is below the “tolerance triangle” requires treatment and is considered as treatment potential (the shaded area in Figure 1).

Observing the increasing tendency of large-scale crises in the interconnected European society and recognizing that there is no common European methodology for resilience assessment, the European H2020 project called IMPROVER (Improved risk evaluation and implementation of resilience concepts to critical infrastructure) was carried out in 2015–2018 (IMPROVER 2018). The main objective of IMPROVER project was to improve European critical infrastructure resilience to crises and disasters through the implementation of combinations of societal, organisational and technological resilience concepts by the development of a holistic methodology based on risk evaluation techniques.

The following case study, as part (Honfi *et al.* 2018) of the IMPROVER project, illustrates the implementation of the IMPROVER Technological Resilience Analysis (ITRA) methodology (Honfi *et al.* 2017).

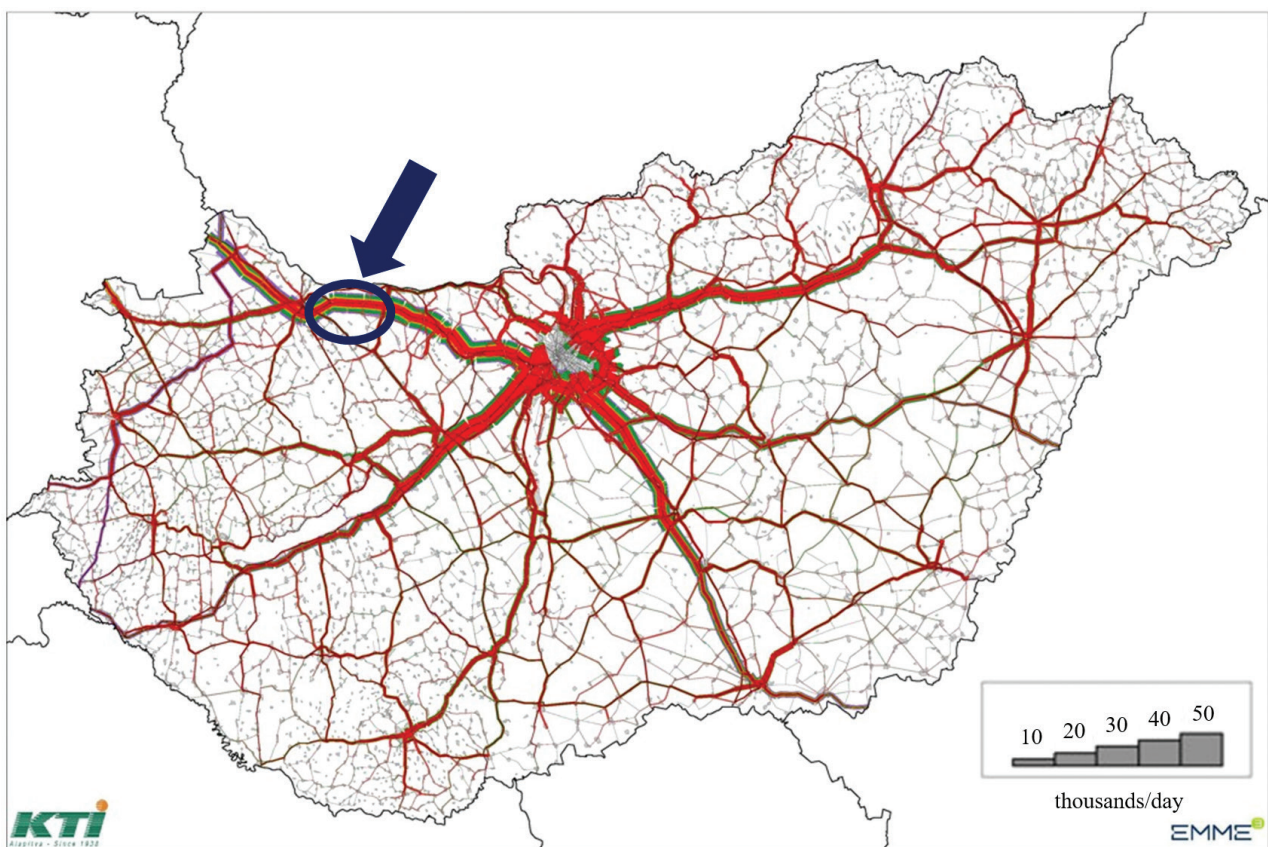


Figure 1 | Resilience triangle
Source: IMPROVER, 2018

Description of the case study

The infrastructure

The M1 Highway is a major toll motorway in north-western Hungary, thus is a transport infrastructure of importance at both national and European scale. It is one of the most important highways in Hungary providing passenger and freight transport between the country's capital, Budapest, and two neighbouring capitals, Vienna in Austria and Bratislava in Slovakia. The traffic volume shown in *Figure 2* confirms the important role of M1 Highway in the highway network. The highway is part of the Pan-European Corridor IV Dresden – Istanbul and part of the E75, E60 and (on a short section) E65 European routes. The M1 highway is operated and maintained by Magyar Közút Nonprofit Zrt. (Hungarian Public Road Non-Profit Plc.), hereinafter Közút.

The studied section is located between km 85 (at the village of Csém, exit Komárom/Kisbér) and km 107 (junction Győr-Kelet; intersection with M19 Highway); it thus spans a length of 21.5 km. The location of the section is indicated in *Figure 2* by an arrow.

Bridges play an important role in the vulnerability of highways. The studied section is crossed by 9 overpass bridges and crosses 1 bridge. The bridges are also maintained and operated by Közút. Relevant data of the bridges are available from the bridge management system (KKK 2001).

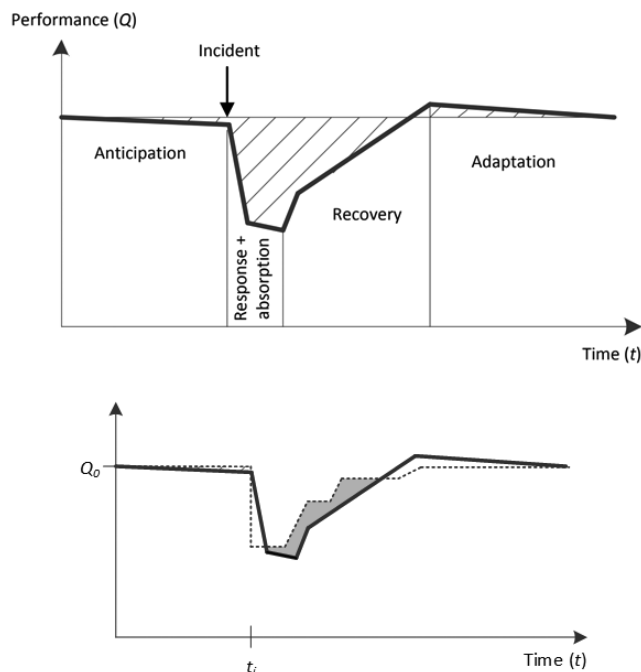


Figure 2 Cross-sectional traffic of national roads in 2008. The studied section is indicated by the arrow.

Source: Magyar Közút, 2016

Performance criteria

The primary function of the M1 highway is to provide uninterrupted traffic of passengers and goods, and in the meantime ensure safety of the users.

Safety of users is seen as a requirement that always needs to be fulfilled and cannot be compromised. Therefore, the performance of the highway is measured here by the benefits it provides to the society. A simplified, but useful indicator is the *travel time* between the selected origin and destination pairs. This could be for example the main entry and exit points of the selected section. It should be noted that this is a function of the actual demands per unit time, say hours or days, for which data is available from the highway operator.

Travel time is a useful indicator for passenger traffic; however, for freight traffic the *travel delay* and the associated *transportation costs* – resulting in *indirect costs* – could also be interesting and can be simplified as proportional to travel distance.

To make use of both indicators, information about the traffic composition is required, i.e. the number of passenger cars vs trucks in the given traffic demand. This can be obtained from existing traffic information and traffic simulation for the studied case.

Another relevant component is the *direct cost* resulted to the event: cost of emergency actions, repair, reconstruction, etc.

Furthermore, an important functional aspect that might be considered is if the road segment is open for emergency services, even if it is closed for the public, to ensure an efficient response in case of disastrous events. This aspect, however, is not explicitly considered in the current report.

The *definition of normal performance* was established together with the highway operator. The highway performance is considered normal if, on the considered section, the highway is fully open for traffic and traffic flow is continuous without queuing. In such a case, the traffic demand is less than the actual capacity of the highway. The capacity of the highway at the studied section is 3400 PCE/h in each direction and the average daily utilisation is 66–75% (Magyar Közút 2016). This was used as a baseline for the study, however, it should be noted that some incidents might even cause a significant increase in the actual demand and resilience could be evaluated accordingly.

As for *user tolerances*, it could be argued that the public have reasonable expectations towards CI operators concerning the infrastructure's performance even during and after crisis situations. Thus, Petersen et al. (2016) suggested that tolerance levels should be determined in terms of "minimum acceptable level of performance" and "acceptable durations of reduced performance". Therefore, an online survey has been carried out to measure the public's tolerance levels for service level reduction and disruption and their duration (Petersen 2018).

Despite being far from representative, the results of the survey have been used for resilience evaluation to demonstrate the methodology.

Resilience analysis

The technological resilience analysis is carried out following the IMPROVER Technological Resilience Analysis (ITRA) methodology discussed in *Honfi et al. (2017)*.

The seismic resilience analysis in the case study is completed through the following steps:

1. seismic risk identification
2. seismic hazard assessment
3. fragility assessment
4. traffic estimates
5. direct and indirect cost calculation
6. risk assessment
7. resilience evaluation
 - user tolerance based resilience evaluation
 - risk-based resilience evaluation
8. resilience treatment

The following sections discuss the analysis.

Seismic vulnerability assessment

Seismic risk identification

Hungary is traditionally considered as low-to-moderate seismic region. However, studying an earthquake scenario is relevant for the operator since most highway

bridges were built before structural design for earthquakes according to Eurocode 8-2 (EN1998-2 2008) became mandatory. For this reason, the impact of the earthquake on bridges and the potential impact on traffic may be important, especially as the section under study is located in the most critical seismic region of the country.

To analyse the vulnerability of the system a detailed analysis of the selected hazards and their direct impact to the physical infrastructure has been studied. They are described as hazard curves for the specific hazards, expressing the probability of exceeding a certain intensity measure and fragility curves of the assets towards a given hazard, which express the probability that a certain damage state will be exceeded for a certain level of the hazard.

Seismic hazard

Seismic hazard can be characterized by the seismic hazard curves indicating the probability of exceedance of given spectral accelerations within a reference period. Due to the fact that all the bridge types are relatively rigid, thus with low fundamental period, good correlation can be found with the peak ground acceleration (PGA) and thus PGA is selected as intensity measure. The reference period is taken as one year (i.e. the risk will be evaluated for a period of one year).

The seismic hazard curves are determined by the probabilistic seismic hazard assessment methodology proposed by the SHARE consortium (*Woessner et al. 2015*). The European seismic source models publicly

Hazard curves

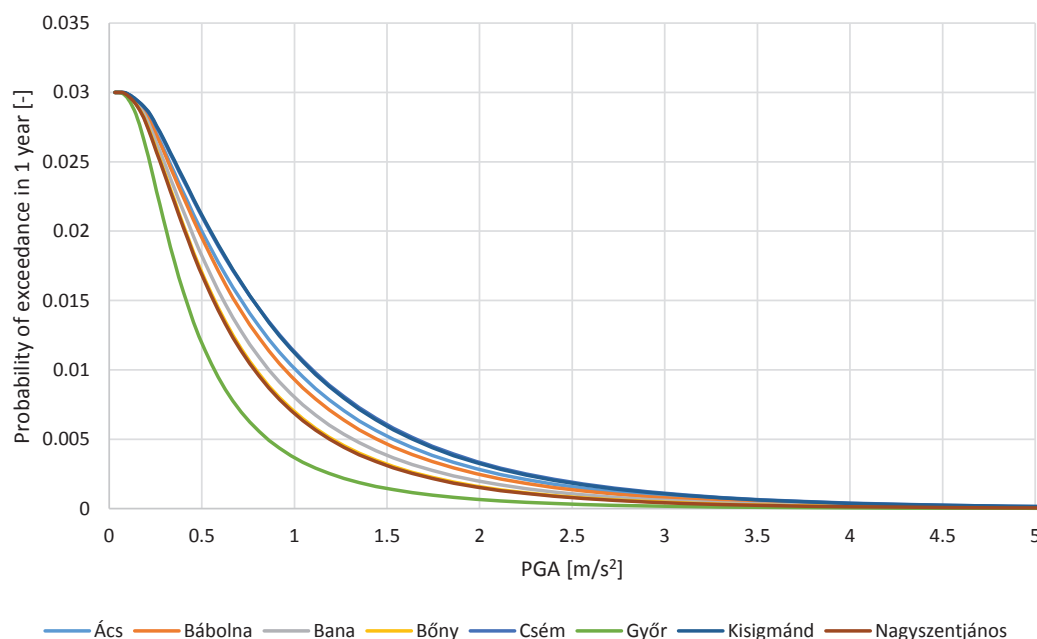


Figure 3

Seismic hazard curves in the investigated area

Source: Vigh et al., 2018

Table 2 | Damage states of bridges

DS	DS description	Remedial actions
DS ₀	No visible damage	nothing
DS ₁	Minor damage (e.g. pier concrete falling out)	repair of piers
DS ₂	Moderate damage (e.g. pier shear deformation)	minor retrofiting
DS ₃	Near collapse	reconstruction, retrofiting, or rebuilding

Source: authors

available at www.efehr.org (EFEHR 2016) are used. Further details about the methodology, the applied tools and results are available in Vigh et al. (2018).

The calculated seismic hazard curves are shown in Figure 3 for various locations around the studied highway section.

Fragility assessment

Earthquake hazard scenario might cause physical damage to the infrastructure assets (bridges, road surface) and the traffic disruption would partly or entirely be a consequence of structural damage. The damages of bridges have the largest contribution to the total risk, and accordingly this study focuses on their representation.

Damages yield to direct costs and risks. Four damage states (DS) are distinguished as listed in Table 2. The definition is based on Priestley et al. (1996) damage limitation (DS1), significant damage (DS2) and near collapse (DS3) consistent with EN1998-2 (2008).

The fragility assessment is completed in accordance with Simon and Vigh (Simon–Vigh 2016, 2018); for a detailed description refer to these papers. Fragility curve shows the conditional failure probability given intensity measure (PGA), for a given damage state. For example, fragility curves for DS₃ damage state (near collapse) are shown in Figure 4 for all the 10 bridges in the area.

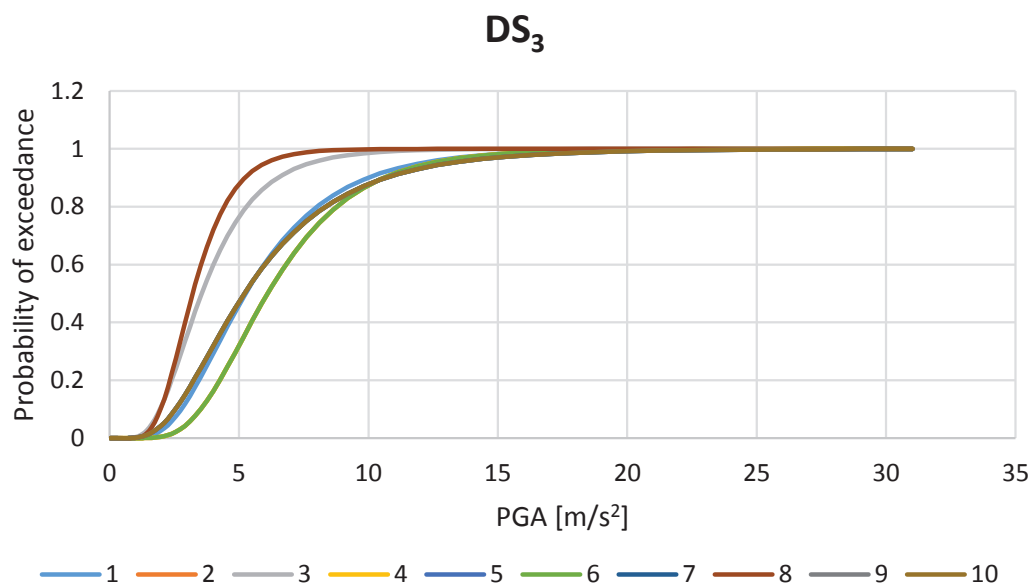
By calculating the product integral of the hazard curve and fragility curve one may obtain the failure probability within the selected – 1 year – reference period.

Seismic risk and resilience assessment

Traffic macro-level estimates

To be able to assess the effect of the earthquake scenarios estimations are needed about the expected traffic situation when the traffic state changes. These estimations need to consider the duration of closures as well as the expected traffic demands. Reasonable assumptions on these macro-level estimates are made together with Kőzút and presented in Table 3.

The outcome of the resilience analysis is illustrated by a few examples. For example, when a major earthquake leads to major damages, i.e. full or partial collapse of the bridge, the studied highway section shall be partially or fully closed for reconstruction activities for a longer period. In such cases, the resilience and the associated risk are dominated by this period instead of the short-term emergency response activities. Figures 5 and 6 show the evolution of traffic flow and delays, as well as the cumulative delay in case of a major earthquake scenario, respectively. The cumulative delay well reflects the resilience of the infrastructure.

**Figure 4** | Fragility curves of different bridge types for damage state DS₃

Source: Simon–Vigh, 2016, 2018

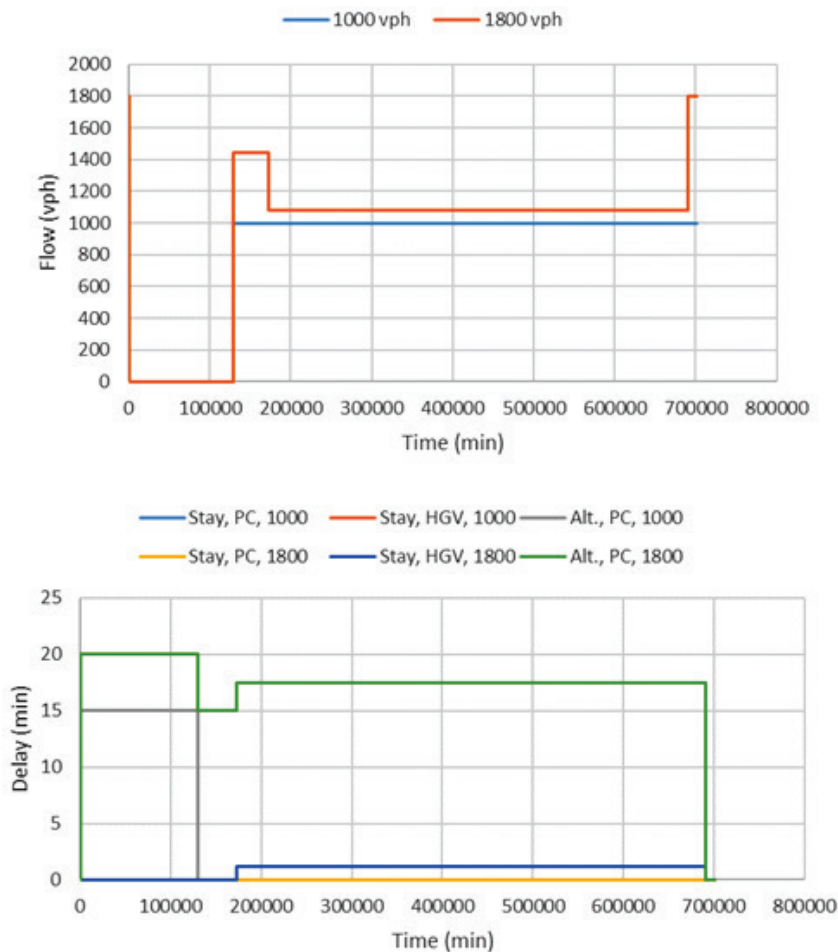
Table 3 | Macro-estimates of traffic parameters

Case	Description	Input flow	Stay on the freeway					Alternative path choice				
			Delay – PC (sec)	Delay – HGV (sec)	Vehs – PC (nr/min)	Vehs – HGV (nr/min)	Vehs – PC (%)	Delay – PC (sec)	Vehs – PC (nr/min)	Delay – HGV (sec)	Vehs – HGV (nr/min)	Vehs – PC (%)
Ma-1	normal flow, 1000 vph	1000	0.0	0.0	13	3	100	0	0	0	0	0
Ma-2	normal flow, 1800 vph	1800	0.0	0.0	24	6	100	0	0	0	0	0
Ma-3	long-term, em. lane closed, 1000 vph	1000	0.0	0.0	13	3	100	0	0	0	0	0
Ma-4	long-term, em. lane closed, 1800 vph	1800	1.8	0.0	19	6	80	900	5	900	0	20
Ma-5	long-term, one lane closed, 1000 vph	1000	0.0	0.0	13	3	100	0	0	0	0	0
Ma-6	long-term, one lane closed, 1800 vph	1800	0.5	1.2	14	6	60	1050	10	1050	0	40
Ma-7	long-term full closure, 1000 vph	1000	0.0	0.0	0	0	0	900	13	900	3	100
Ma-8	long-term full closure, 1800 vph	1800	0.0	0.0	0	0	0	1200	24	1200	6	100
Ma-9	short-term, em. lane closed, 1000 vph	1000	0.0	0.0	13	3	100	0	0	0	0	0
Ma-10	short-term, em. lane closed, 1800 vph	1800	1.8	0.0	19	6	80	900	5	900	0	20

Remarks:

Ma-1, Ma-2: no delay; Ma-3: no delay, one lane can transfer the whole traffic flow; Ma-4: minor delay on freeway, alternative route (only PC): 15 min delay for PC; Ma-5: no delay, one lane can transfer the whole traffic flow; Ma-6: minor delay on freeway, alternative route (only PC): 18 min delay for PC; Ma-7: alt. route: both PC and HGV, 15 min delay for passenger vehicles and HGV; Ma-8: alternative route: both PC and HGV, 20 min delay for passenger vehicles and HGV; Ma-9: no delay, one lane can transfer the whole traffic flow; Ma-10: minor delay on freeway, alternative route (only PC): 15 min delay for PC.

Source: authors

**Figure 5** | Evolution of traffic flow and delays (major earthquake)

Source: authors

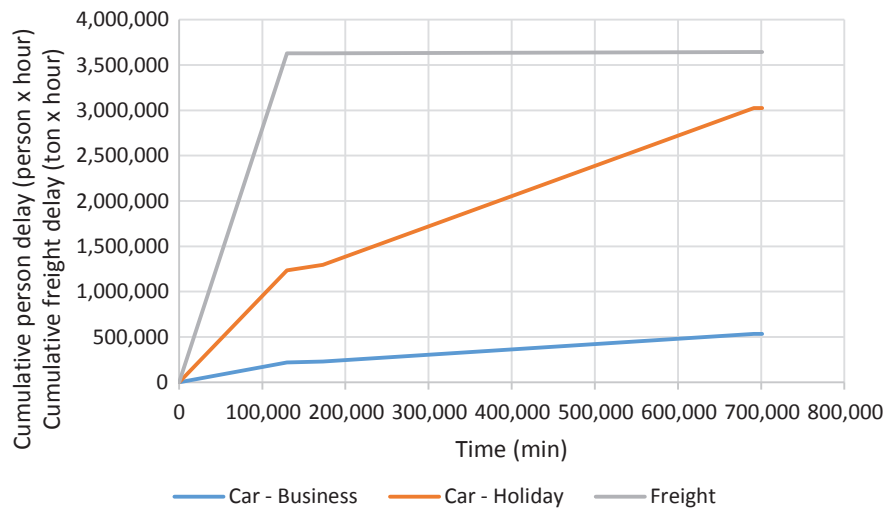


Figure 6 Cumulative delays (major earthquake)
Source: authors

Resilience evaluation based on user tolerance

The evaluation of passenger delays is carried out through a comparison with the “tolerance functions” constructed based on the online survey (Petersen 2018). As an example, Figure 7 compares user tolerances and expected delays for the major earthquake scenario (DS₃). It is demonstrated that the calculated performance loss and recovery function (delay function) exceeds the “tolerance curve”, and thus it requires treatment.

Risk-based resilience evaluation

Risk assessment requires the cost analysis of direct consequences (emergency responses, restoration costs) and indirect consequences (e.g. delay costs).

Direct costs are primarily related to the reconstruction of the bridges and the vicinity of the bridges, and do not include costs related to possible derivative accidents. Indirect (delay) costs are based on VTTs (value of travel time savings) values. Unit time values can be determined on the basis of the data of HEATCO (2006). Based on the economical surplus calculation the process of expressing the total travel time saving and freight traffic benefit in monetary terms are the followings:

- for passengers: travel time saving × unit value of time,
- for freight traffic: freight tonne/hour saving × unit value of freight transport.

Risk is calculated as the product of failure probability and consequence cost.

The cost and risk calculation for a major earthquake scenario (DS₃) and for all the damage states are summa-

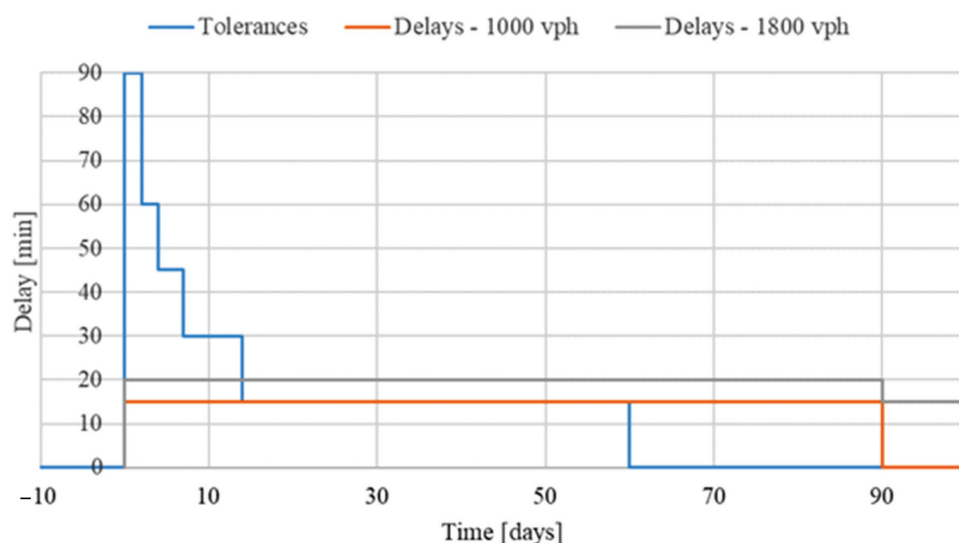


Figure 7 User tolerances vs expected delays, earthquake scenario, DS₃
Source: authors

Table 4 | Cost and risk analysis for major earthquake scenario

DS	Flow	Delay cost								Failure probability per year	Delay risk
	(vph)	Passenger delay					Freight delay		Total		
		Business		Holiday		Total					
		(p x h)	€	(p x h)	€	€	(t x h)	€	€	(-)	€
DS ₃	1000	90,720	2,029,919	514,080	5,187,882	7,217,800	1,512,000	4,981,883	12,199,683	0.0004	4,369
	1800	533,733	11,942,625	3,024,488	30,521,874	42,464,499	3,642,759	12,002,512	54,467,011	0.0011	58,511

DS	Bridge #	Failure probability per year	Direct cost €	Direct risk €	Total direct risk €	Total Risk €
DS ₃	1	0.000553	1,235,200	683	6,030	68,910
	2	0.000265	1,235,200	328		
	3	0.001432	1,235,200	1,769		
	4	0.000217	1,235,200	268		
	5	0.000581	1,235,200	718		
	6	0.000217	1,235,200	268		
	7	0.000308	1,235,200	381		
	8	0.000690	1,235,200	853		
	9	0.000308	1,235,200	381		
	10	0.000308	1,235,200	381		

Source: authors

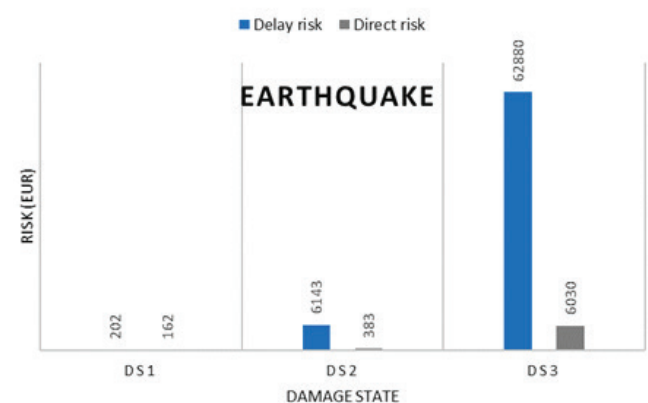
ized in Table 4 and Figure 8, respectively. The results confirm that earthquake in general could be considered as a low risk. From the figure, it could be concluded that increasing resilience towards earthquakes could involve measures which improve the fragility of the bridges against major earthquakes to avoid loss of overall structural integrity. It seems more efficient, however, to reduce the indirect effects resulting in user delays, e.g. by improving recovery in the aftermath of a major earthquake event.

Resilience treatment

In general, to develop efficient resilience treatment strategies, the investment costs of upgrading the bridges or reducing the expected performance loss should be compared and/or combined with the calculated risks. It should be analysed how various investments reduce the estimated risks by reducing either failure probabilities or consequences (the third component, the probability of occurrence of seismic event cannot be altered). Some possible strategies for resilience treatment therefore include the following:

- Improvement of the fragility of the bridges:
 - strengthening of critical structural elements;
 - increasing the overall structural robustness, i.e. overall damage tolerance and susceptibility to disproportionate collapse tolerance.
- Reduction of clearance and recovery times:
 - techniques for quick and efficient damage identification using e.g. structural health monitoring;

- application of accelerated bridge demolition and construction technologies for the reconstruction of the bridges at DS3 scenarios to effectively reduce the clearance and recovery times;
- application of early warning system to allow for fast response.
- Improving knowledge:
 - it should be appreciated that more credible modelling approaches might give different results. Therefore, improving both the emergency response and recovery models could virtually increase the overall resilience. To reach this data from previous incidents need to be collected, stored and analysed systematically and continuously.

**Figure 8** | Risk for earthquake scenario

Concluding remarks

This paper describes the seismic technological resilience assessment of a particular section – namely the section from km 85 to km 107 km (between Csém and Győr) – of the M1 Highway in Hungary.

The assessment follows the ICI-REF framework (IMPROVER Critical Infrastructure Framework) which, within the IMPROVER project, has been developed to be integrated with the risk management process of ISO 31000. The framework allows for various methodologies to assess critical infrastructure resilience.

This study demonstrates the IMPROVER technological resilience analysis (ITRA) focusing on the resilience of the physical assets of the highway and highlights both: 1) the novelty of the approach by directly measuring resilience against the community's (i.e. the highway users) tolerances, and 2) the links to traditional risk assessment by using a risk-based resilience evaluation to indirectly account for the broader society's willingness to invest into resilience improvement (primarily concerning the management of the highway's assets such as bridges).

In the resilience analysis part of the paper, a detailed description is given about the application of emergency response and recovery models involving traffic simulations. The aim is to calculate the time evolution of the expected user delays for the various analysed scenarios and summarize the resulting expected costs until final recovery. The evaluation of resilience is based on two approaches: 1) comparison with user tolerances, and 2) risk-based evaluation of resilience. The results suggest that technological resilience could be improved.

In the final part of the paper resilience treatment options are highlighted. First, through the results of the user tolerance-based evaluation the possible treatment of long recovery times is discussed. Then, by the risk-based evaluation approach, prioritization of investments for enhancing resilience is discussed.

Development of complex resilience treatment strategies for the highway, however, should rely on findings from the other methodologies, such as the organisational analysis (IORA) and the holistic self-assessment (tool CIRI) tools, developed within IMPROVER.

Acknowledgement

The presented work is accomplished in and supported by the H2020 project called IMPROVER (Improved risk evaluation and implementation of resilience concepts to critical infrastructure, H2020 Grant agreement ID: 653390).

Completion of the work would not have been possible without the support and active contribution of the highway's operator, Magyar Közút Nonprofit Zrt. Hereby, the authors would like to express their appreciation for their help and enthusiasm.

Further development is supported by the project no. BME-NVA-02, implemented with the support provided by the Ministry

of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021 funding scheme.

References

2011. évi CXXVIII. törvény a katasztrófavédelemről és a hozzá kapcsolódó egyes törvények módosításáról
2012. évi CLXVI. törvény a létfontosságú rendszerek és létesítmények azonosításáról, kijelöléséről és védelméről
- 65/2013. (III. 8.) Korm. rendelet a létfontosságú rendszerek és létesítmények azonosításáról, kijelöléséről és védelméről szóló 2012. évi CLXVI. törvény végrehajtásáról
- 161/2019. (VII. 4.) Korm. rendelet a közlekedési létfontosságú rendszerek és létesítmények azonosításáról, kijelöléséről és védelméről
- 249/2017. (IX. 5.) Korm. rendelet az infokommunikációs technológiák ágazathoz kapcsolódó létfontosságú rendszerek és létesítmények azonosításáról, kijelöléséről és védelméről
- 234/2011. (XI. 10.) Korm. rendelet a katasztrófavédelemről és a hozzá kapcsolódó egyes törvények módosításáról szóló 2011. évi CXXVIII. törvény végrehajtásáról
- 1249/2010. (XI. 19.) Korm. határozat az európai kritikus infrastruktúrák azonosításáról és kijelöléséről, valamint védelmük javítása szükségességének értékeléséről szóló, 2008. december 8-i 2008/114/EK tanácsi irányelvnek való megfelelés érdekében végrehajtandó kormányzati feladatokról
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... von Winterfeldt, D. (2003) A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, Vol. 19. No. 4. pp. 733–752.
- CEN (2008) EN 1998-2 Eurocode 8: Design of structures for earthquake resistance. Part 2: Bridges.
- CIWIN (2013) https://ec.europa.eu/home-affairs/networks/critical-infrastructure-warning-information-network-ciwin_en
- EFEHR (2016) European Facilities for Earthquake Hazard & Risk. <http://www.efehr.org> [last visited: August 2016].
- European Council Directive (2008) Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. *Official Journal of the European Union*, 23 December 2008.
- Gyenes Zs. (ed. 2011) Nemzeti katasztrófabiztonság-értékelés. BM Országos Katasztrófavédelmi Főigazgatóság.
- HEATCO (2006) Developing harmonized European approaches for transport costing and project assessment. HEATCO.
- Honfi, D., Lange, D., Malm, A., Mindykowski, P., Alheib, M., Bouffier, C., ... Röd, B. (2017) Technological resilience concepts applied to critical infrastructure. IMPROVER project deliverable D3.2
- Honfi, D., Lundin, E., Sjöström, J., Lange, D., Vigh, L. G., Petersen, L., & Ioannou, I. (2018) Report of technological resilience concepts applied to living labs. IMPROVER project deliverable D3.3.
- IMPROVER (2018) IMPROVER (Improved risk evaluation and implementation of resilience concepts to critical infrastructure, H2020 Grant agreement ID: 653390).
- KKK (2001) EHR: Egységes Hídnilyvtartási Rendszer (Bridge Inventory Database).
- Magyar Közút (2016) Az országos közutak 2015. évre vonatkozó keresztmetszeti forgalma. Magyar Közút, November 2016.
- National Directorate General for Disaster Management. <https://www.katasztrofavedelem.hu/>
- Petersen, L. (2018) M1 Highway Questionnaire Results, IMPROVER project, European Commission H2020.

- Petersen, L., Fallou, L., Reilly, P., Serafinelli, E., Carreira, E., & Utkin, A. (2016) Social resilience criteria for critical in-frastructures during crises. IMPROVER project, Deliverable 4.1, European Commission H2020.
- Petersen, L., Sjöström, J., & Horvath, E. (2019) Evaluating critical infrastructure resilience via tolerance triangles: Hungarian Highway pilot case study. *Proceedings of the International ISCRAM Conference*, pp. 1210–1225.
- Priestley, M. J. N., Seible, F., & Calvi, G. M. (1996) *Seismic design and retrofit of bridges*. New York, NY, John Wiley & Sons, Inc.
- Pursiainen, C., Bjarte, R., Baker, G., Honfi, D., & Lange, D. (2016) Critical Infrastructure Resilience Index. Risk, reliability and safety: innovating theory and practice - *Proceedings of the 26th European Safety and Reliability Conference (ESREL 2016)*.
- Simon J., & Vigh L. G. (2016) Seismic fragility assessment of integral precast multi-span bridges in areas of moderate seismicity. *Bulletin of Earthquake Engineering*, Vol. 14. No. 11. pp. 3125–3150.
- Simon J., & Vigh L. G. (2018) Seismic reliability assessment of typical road bridges in Hungary. *Journal of Earthquake Engineering*, Vol. 22. No. 10. pp. 1758–1786.
- Tierney, K., & Bruneau, M. (2007) Conceptualizing and measuring resilience: a key to disaster loss reduction, TR news 250. *Transportation Research Board*, pp. 14–15.
- UNISDR (2009) 2009 UNISDR terminology on disaster risk reduction. *United Nations International Strategy for Disaster Reduction (UNISDR)*. Geneva, Switzerland, May 2009.
- Vigh L. G., Zsarnóczay Á., Simon J., Mahler A., & Bán Z. (2018) Helyi spektrumok alkalmazása földrengésre történő méretezésre. Budapest, Magyar Mérnöki Kamara.
- Woessner, J., Danciu, L., Giardini, D., Crowley, H., Cotton, F., Grünthal, G., ... Stucchi, M., and the SHARE Consortium (2015) The 2013 European Seismic Hazard Model: key components and results. *Bulletin of Earthquake Engineering*, Vol. 13. pp. 3553–3596. DOI: <https://doi.org/10.1007/s10518-015-9795-1>