16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 1995
Registration Code: S-XXXXXXXX

ROBUSTNESS OF BRIDGES FOR EMERGENCY FUNCTIONALITY OF ROAD NETWORKS UNDER MULTIPLE EXTREME EVENTS

U.E. Dorka[(1)]

[(1)] *Professor, Universität Kassel, Kassel, Germany, uwe.dorka@uni-kassel.de*

Abstract

Extreme earthquakes like the Nankai Trough scenario will trigger further hazards that may affect already damaged bridges, like landslides, fires or tsunami. Bridges are the backbone of road networks and must provide a minimal functionality after such a sequel of events, which they are typically not designed for. This requires a certain “robustness”, which in this context may be defined as a required “residual functionality” of a damaged bridge. This residual functionality is the type and amount of traffic that the bridge has to be able to accommodate after the event sequence in order to support the necessary emergency and evacuation activities. It depends on the role of the bridge within the road network.

This paper presents a road map to such robustness of bridges under multiple events that are triggered by extreme earthquakes. It addresses the importance of hazard sequencing (earthquake followed by tsunami, land slide, fire etc.) and discusses the reduction of functionality due to certain damage types (e.g. pier damage due to shear, un-seating of bearings, permanent soil deformation etc.). In this context, it is recognized that some damage types lead to zero functionality. This leads to a definition of “acceptable” and “un-acceptable” damage states for high-impact bridges.

Considering only ground shaking, un-acceptable damage states can be avoided in general by selecting proper structural systems, in particular seismic control concepts like the Hyde System, which not only provides this “robustness” but is also an economic retrofitting solution for deck bridges, the most common type in todays road networks. In the case of landslides and tsunami, robustness may be achieved with known and even simple concepts, but this needs further study. The hazard from un-controlled fire under such circumstances is largely unknown and needs further study before reasonable and economic measures towards fire robustness can be developed.

A combination of traffic management tools (especially agent-based simulations) is able to identify bridges that are critical for emergency response and evacuation. They need realistic estimates of residual emergency functionality, which in turn is a function of the remaining load bearing capacity. ROADERS (Road Networks for Earthquake Resilient Societies), an international network of researchers in bridge engineering and traffic management provided a first framework how to approach this. Pre-disaster structural studies must be performed and validated for various levels of damage in order to obtain a realistic picture of a bridge’s remaining functionality. This information can then enter advanced and dynamic disaster management systems (like IDDSS) to allow realistic agent-based simulations for well-informed decision making within minutes.

This may be required especially for emergency evacuation when, like for Osaka, only 30 minutes are available before the tsunami arrives.

Keywords: emergency functionality; robustness of bridges; multiple hazards; seismic control; agent-based simulation

1. Introduction

"Road Networks for Earthquake Resilient Societies" (ROADERS) was a network of international researchers and road network operators financed through the European ERA-NET CONCERT. CONCERT was established to identify areas of common research interests between Europe and Japan. The partners in ROADERS were:

CONCERT financed partners:

Eiichi Taniguchi, Kyoto University, Japan, **Project Leader Japan**
Uwe E. Dorka, Universität Kassel, Germany, **Project Leader Europe**
Gabriela M. Atanasiu, Technical University "Gheorghe Asachi" of Iasi, Romania
Toshiro Hayashikawa, Hokkaido University, Sapporo, Japan

Self-financing partners:

Russell G. Thompson, University of Melbourne, Australia
Panagiotis Angeloudis, Imperial College London, UK
Shigeru Matsumoto, Hanshin Expressway Company Ltd, Japan
Constantin Zbarnea, Directia Regionala Drumuri si Poduri Iasi, Romania

The resilience of road networks under worst-case seismic events, especially when additional hazards are triggered (post-quake fires, landslides, tsunamis and a series of large aftershocks), is poorly understood. Current reliability-based planning and design methods for road networks and their critical components do not address resilience, which, in this context, may be interpreted as required residual functionality and timely recoverability after a sequence of "highly unlikely but possible" events that exceed the design limit. Methods to assess and improve this resilience are largely missing or in an early stage of development (like multi-agent simulations to assess post-disaster needs for transport or more robust structural concepts for critical components like bridges)

The overall aim of ROADERS was to provide a rational framework for the assessment and improvement of the resilience of road networks subjected to worst-case earthquakes that trigger additional hazards. To this end, the potential of

- post-disaster simulation methods based on agents (residents, decision makers, etc.) to identify the required residual functionality of a road network and its critical components, especially bridges.
- advanced structural concepts (especially for bridges), to provide robust behaviour beyond their regular design limit to ensure the required residual functionality.
- innovative repair methods for conventional bridges (in particular elevated roads) to provide timely functional recovery

were investigated and a rational approach for the most appropriate selection of a combination of improvements (structural, topological and traffic management) using resilience-based optimization was provided.

Two unlikely but possible earthquake scenarios were defined, one for the Osaka region of Japan and one for the North-Eastern region of Romania, around Iasi. Both were based on "tectonic possibilities" rather than statistical seismic models.

Based on these, the structural performance of major components of the existing networks was estimated considering accumulating hazards (liquefaction, landslides, fires, tsunami) to provide a realistic basis for the following methodological studies on resilience.

To estimate post-disaster transport requirements, the needs and behaviour of the agents (residents, administrative bodies, rescue organisations etc.) must be understood. This includes immediate transportation needs (e.g. unorganised evacuation, search and rescue or emergency medical services, etc.) as well as transport needs during the period of recovery (debris removal, intense rebuilding, changes in regional planning etc.). The aim was to understand factors influencing these needs such as geography, population density, location of command and evacuation centres and in particular *social capital*, which in this context is the capability of a community for self-organisation.

Based on the estimated transport requirements and damage estimation, selected critical components, in particular bridges were investigated in terms of their residual transport capacity and recovery time. Innovative robust structural concepts were explored, such as retrofitting or renewal of bridges using structural control systems. In addition, innovative rapid post-disaster repair methods for common bridge structures, such as concrete frames in elevated roads, were explored.

This paper provides an overview of the ROADERS studies on robustness of bridges as required by emergency transport needs around Osaka stemming from the Nankai Trough Scenario. More in-depth information and additional studies (e.g. with respect to the Romanian situation) can be found in the proceedings of the four ROADERS workshops, which can be downloaded from the following website: http://florinleon.byethost24.com/mcserm/en/resultsroaders.htm.

2. Osaka and The Nankai Trough Scenario

The Nankai Trough scenario [1] is based on tectonic "possibilities" rather than statistical evidence. It considers a rupture of the Nankai Trough in front of Osaka Bay creating an earthquake and tsunami similar to the Tohoku event of 2011 (Fig.1).

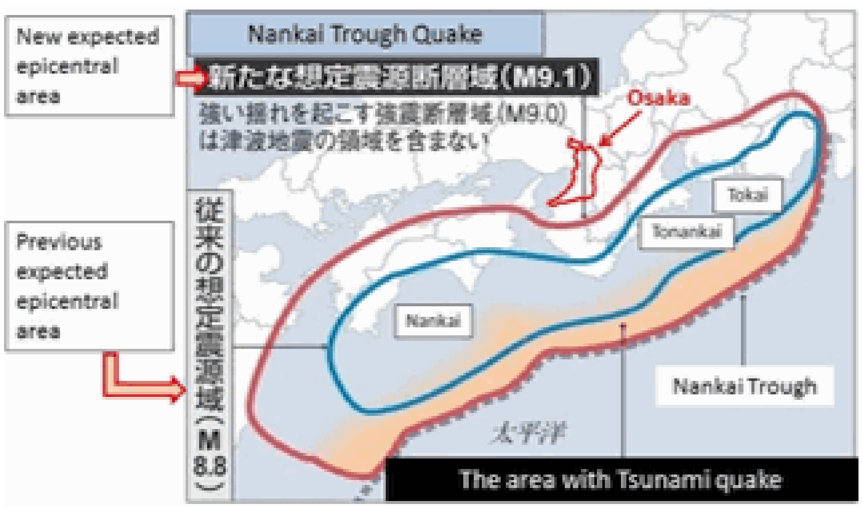


Fig. 1 – Epicentral area of the Nankai Trough scenario [1].

This event will affect a densely populated area with a well maintained road network that features several hundred kilometers of elevated roads, mostly around Osaka Bay and thus close to the sea. Next to tsunami, there is a large-scale soil liquefaction hazard and fire hazard due to burning tanker trucks on or below bridges, with little chance of fire fighting immediately after the event. Landslides are less of a problem except in the mountains behind Kobe and east of Osaka, where population density is low.

For immediate rescue and evacuation, a part of Osaka's road network has been designated as "Emergency Road Network" (Fig.2) [2] requiring a minimum functionality after the Nankai Trough event. These are mainly conventionally built elevated roads. They are to be used with priority by emergency vehicles (ambulances, fire engines etc.) rushing to the scene and not by people fleeing the area, especially from the imminent tsunami.

There are tsunami shelters close to the coast and within the expected inundation area, but they cannot accommodate all the population present in these areas. This requires the use of secondary roads for evacuation with a few older bridges connecting the islands to the main land. It also requires for many to flee on foot.

To obtain an idea of the transport demand during evacuation, an evacuation study was performed in ROADERS for the Minato Ward under the leadership of the team from Kyoto University [3].

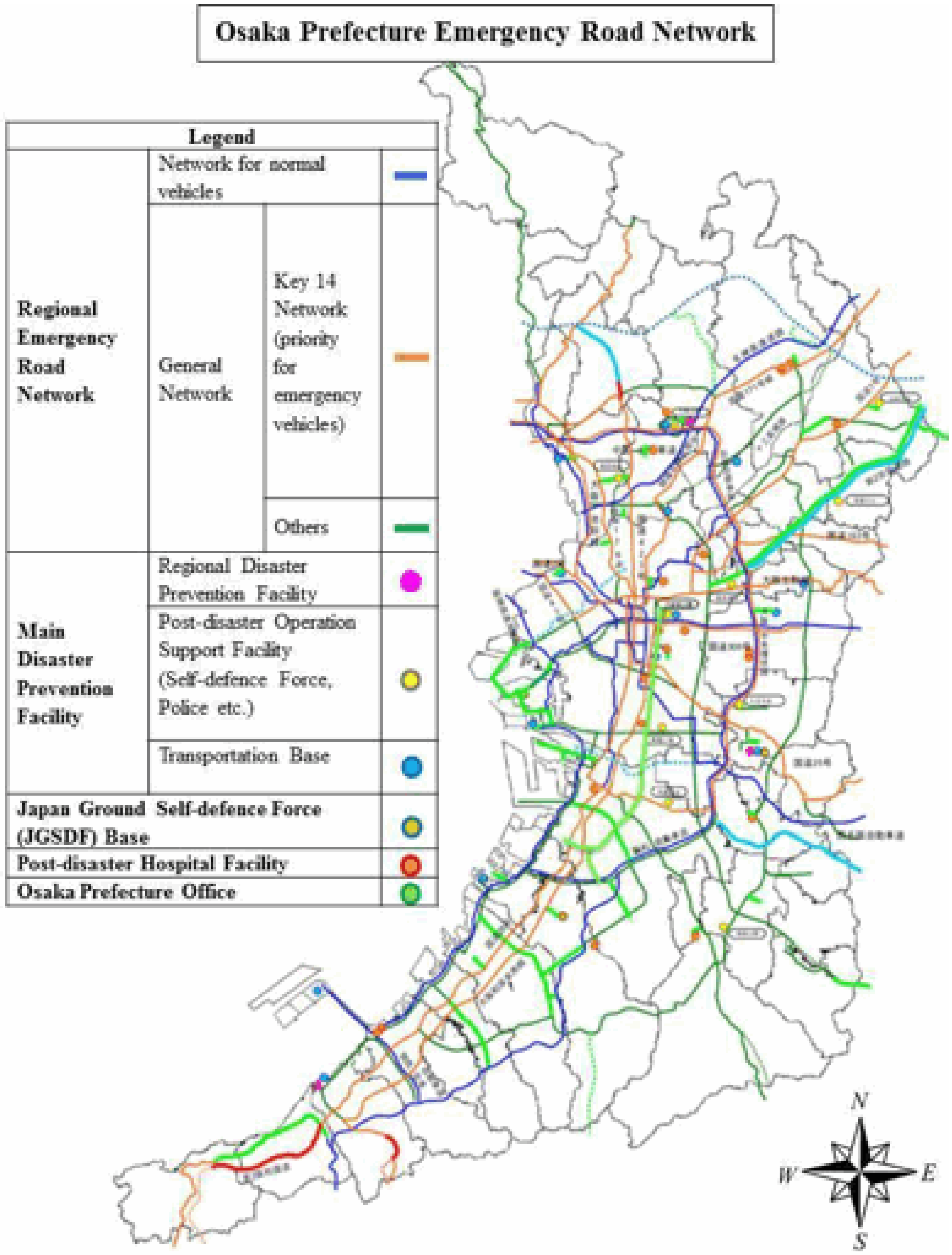


Fig. 2 – Osaka's road network designated for emergency response [2].

This ward faces a particular risk of inundation due to tsunami, which may arrive about 30 min after the earthquake. The tsunami shelters in Minato can accommodate only about half of the population of 80000. This requires the use of outside shelters. Reaching those may be hampered by earthquake damage to a number of bridges (Fig.3).

The study was performed using "multi-agent simulations". This allows the analysis of systems based on realistic behaviour of various stakeholders inclusive of their "social capital", which refers to resources available to individuals through their social networks. The agent perspective on modelling relies on the point of view of the individuals, which comprise the system and consider their individual rules for decision-making. Each agent can be activated depending on scenarios and time lapse after the disaster occurred. For instance, people who are trapped or injured would be waiting for rescue personnel and medical treatment creating rescue demand on site, while others may start to evacuate to shelters. On the other hand, government officials make top decisions to manage the overall demand based on fuzzy information received from other agents. This creates a rather complex framework for post-disaster simulation.

The "ROADERS Evacuation Simulation Software" REvaSim [4] is based on this framework. One way of reducing complexity is to introduce "granularity". Agents are now groups of people rather than individuals, and the size of the groups is a simulation parameter: it can vary from 1 (fine-grained simulation) to 100 or more individuals (coarse-grained simulation). The simulation is time-based, using a discrete model. In each time step, the agents make decisions whether to evacuate or not and if they are in the process of evacuation, they decide on which path to follow, in a greedy approach, i.e. they choose the path that represents the shortest time to reach a shelter. Their social capital influences these decisions e.g. in the form of government advice and the behaviour of their neighbours. In addition to active agents (government decision makers, groups of evacuees) there are also passive agents (road links, shelters) implemented in the software.

The study tested the effect of social capital on evacuation in the form of following either government advice ("Advice" case) or that of others (neighbours, people on the streets etc.: "Field" case). In the "Advice" case, the evacuees located near the coast are told to move inland instead of occupying the tsunami shelters nearby and those nearer the borders of Minato Ward are told to move to neighbouring wards due to the limited capacity of the tsunami buildings. In the "Field" case, at least half of the inland population of Minato Ward away from the risk point were assumed to have a higher threshold against risk. In both cases a 50% residual transport capacity was assumed for all bridges.

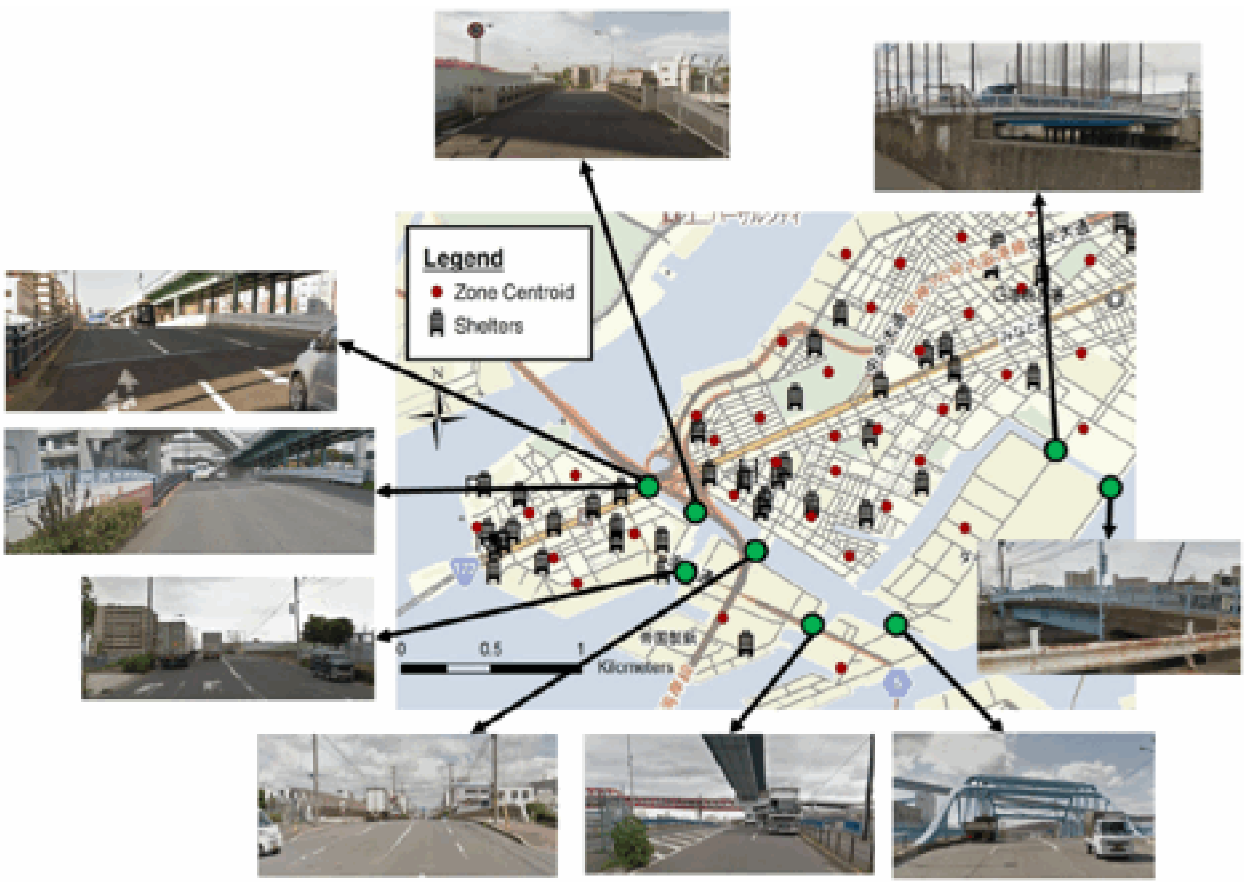


Fig. 3 – Minato Ward in Osaka with bridges and tsunami shelters. Shelters near the coast are to the far left [3].

As expected, the "Advice" case gives a better performance, with all evacuees reaching their shelter in time (less than 30 min) whereas in the "Field" case, only about half of them make it to safety. An interesting behaviour is observed for the “Field” case where there is an increase of evacuees in the tsunami risk area after 15 minutes. This may be caused by the lack of shelter capacity information at the initial stage of evacuation (Fig.4).

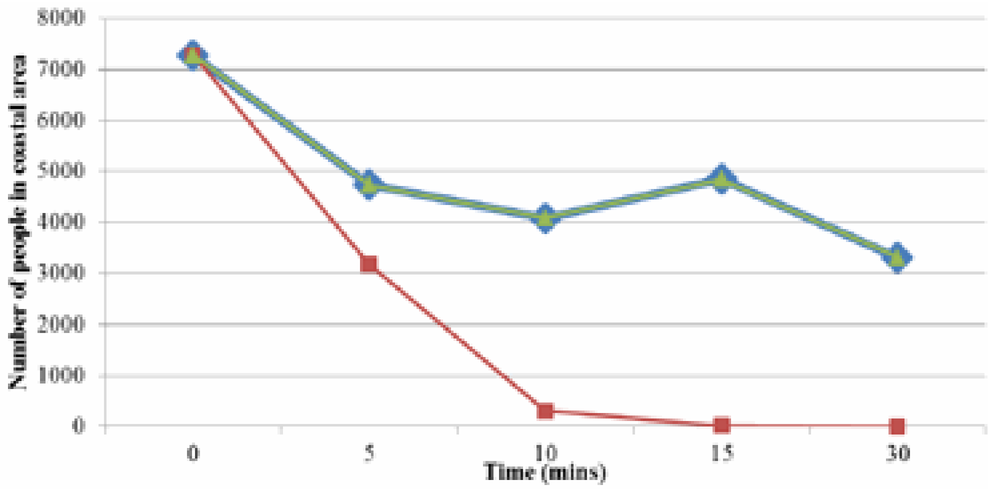
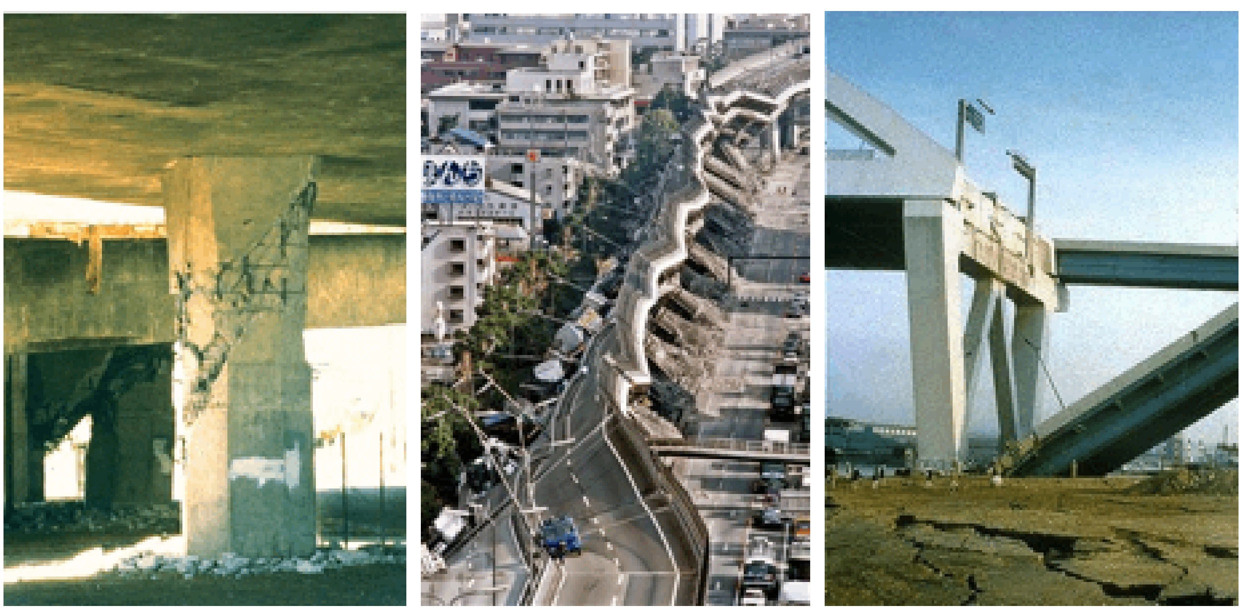


Fig. 4 – Number of people remaining in tsunami risk areas. Red: “Advice” case, green-blue: “Field” case [3].

A 50% reduction in overall bridge transport capacity does not seem to have a decisive effect on the simulation results. The picture will be different, if certain bridges experience a total loss in functionality. This will lengthen certain escape routes and may even cut off a number of people from designated shelters. Thus, even in the “Advice” case, a minimum functionality of critical bridges must be assured. That depends on the kind of damage that they may be allowed to sustain.

3. Damage Scenarios for Bridges under Accumulating Hazards



EERI slide collection, Northridge www.worldpress.com www.ce.whashington.edu

Fig. 5 – Typical earthquake damage on bridges leading to zero functionality. From left to right: shear failure of piers, toppling of piers, drop-off of super structure [5].

The initial effect of the earthquake (including soil liquefaction) may cause failures that typically result in zero functionality (Fig.5):

– Shear failure of piers due to over-load
– Toppling of piers due to excessive overturning (P-Δ effect)
– Drop-off of super structure due to bearing failure or movement of piers (foundation failure, e.g. liquefaction or pile buckling)

These failures demonstrate an exceedance of the design limit, which was not set to accommodate the event that occurred. The performance of these bridges is such that, once the design limit is exceeded, failure may occur immediately and suddenly.

EERI Tohoku clearing house

Proc. 1st ROADERS Workshop, Iasi-Kyoto, 2013

Fig. 6 – Floating-off of decks and scouring around piers may occur during a tsunami [5].

Scouring around piers and floating-off of superstructures has been observed during tsunami (Fig.6). Floating-off can occur because of trapped air underneath the deck causing enough uplift for the deck to float like a ship resulting in zero functionality. Scouring is due to high flow velocity and the presence of debris, especially during back-flow. In many cases, a residual functionality can be expected even if the damage seems to be severe. The debris may also pile up against a low bridge deck exerting considerable horizontal force, which may lead to bearing failure and subsequent drop-off.

www.bakersfieldnow.com

EERI slide collection, Kobe

Fig. 7 – Burning tanker trucks or houses close to bridges can result in zero functionality [5].

Fires can cause damage to or collapse of bridges mainly from underneath. Particularly dangerous are tanker trucks (Fig.7, left) and mass collisions, which may occur during an extreme earthquake event. In both cases a large combustion mass is available because of highly flammable fuels. These may seep through bridge joints causing fires underneath although the vehicles may be on top. In addition to this, buildings close to an elevated road may catch fire. In both cases, fires may rage for several hours with temperatures that can cause collapse. Even if no collapse occurs, fire will damage the material, especially concrete and can produce large deformations, especially buckling in steel members due to the reduction in stiffness and strength during high temperatures. Steel may recover these properties after the fire, but usually in a highly deformed state. Concrete cannot recover its strength once it is reduced by fire since cracking (even difficult to detect micro cracks) will occur.

EERI Kumamoto clearing house EERI Kumamoto clearing house

Fig. 8 – Bridge failure due to land slides during the April 2016 Kumamoto event: Choyo Bridge abutment failure (left) and displaced piers of Toshita Bridge (right)

Landslides may affect piers and abutments, especially if the initial movement takes place around or underneath these structures (Fig.8). This can cause large displacements and rotations of the foundations that may result in a drop-off of a superstructure and thus zero functionality. A landslide hitting a pier may also displace it, if enough mass is in motion. These scenarios are not well understood and further studies are needed here.

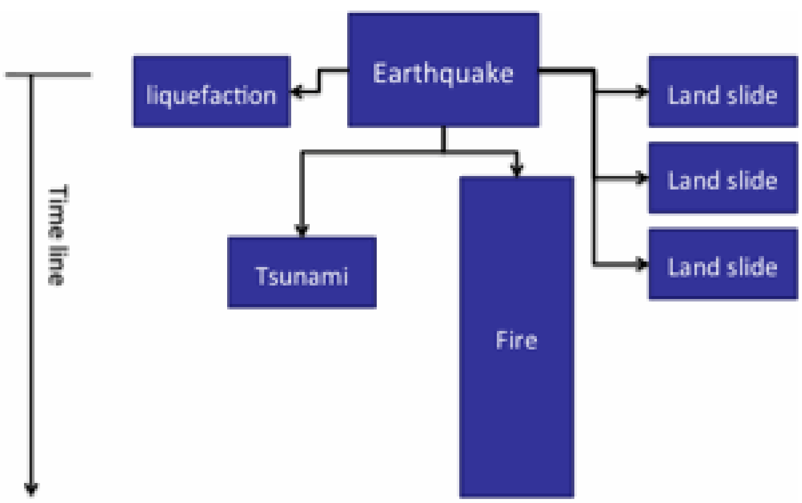


Fig. 9 – Basic sequel of hazards triggered by an earthquake. The type and size of each hazard and its timing depends strongly on the location of the bridge, even within a given scenario [5].

Considering all the hazards triggered by an extreme event eventually will allow the establishment of a hazard sequel with a time line for a particular bridge (Fig.9). This sequel can be very different for different bridges even within the same area and for the same earthquake scenario. Once established, it allows for a first assessment of a possible damage sequence. It is obvious that, seemingly similar bridges may sustain very different damages, which will affect their functionality and that of the whole network.

4. Robustness of Bridges under Multiple Extreme Events

Considering the ambiguities of a hazard sequel (Fig.9) and the lack of knowledge concerning the damage it may cause, bridges (and in particular deck bridges in elevated roads) must be able to perform beyond their design limit, if emergency functionality is required. This leads to a definition for "robustness" of bridges under multiple extreme events [5]:

Subjected to a hazard sequel triggered by an extreme earthquake, a bridge must secure a minimal functionality beyond its design limit

This request for "robustness" requires a classification of damage, e.g. whether a certain type of damage is acceptable or not. This can be based on the required residual functionality after the damage has occurred. If the functionality is zero, this type of damage is clearly un-acceptable and must be prevented.

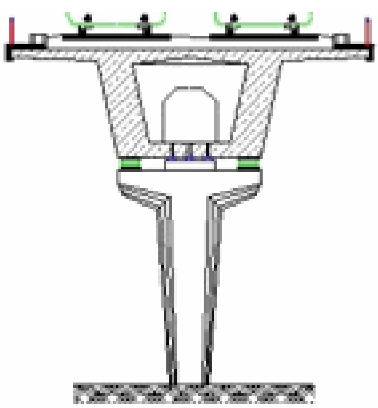
Any substantial failure of piers or drop-off of a superstructure leads to zero functionality and thus is un-acceptable. On the other hand, un-seating of a bearing or a restricted movement of a pier or abutment, which still provides some emergency functionality is acceptable. So is scouring around pile foundations or a reduction in section capacity due to fire as long as the remaining load bearing capacity is sufficient for emergency functionality.

Un-acceptable damage:

– Drop-off or floating off of decks or larger sections
– Failure of piers or abutments: foundation failure, toppling or shear failure

Acceptable damage:

– Limited movement of piers and abutments without drop-off of decks
– Scouring of pier foundations without substantial loss of load carrying capacity
– Un-seating of bearings without section drop-off
– Limited reduction of section capacity due to local damage (fire, accidents, earthquake damage)



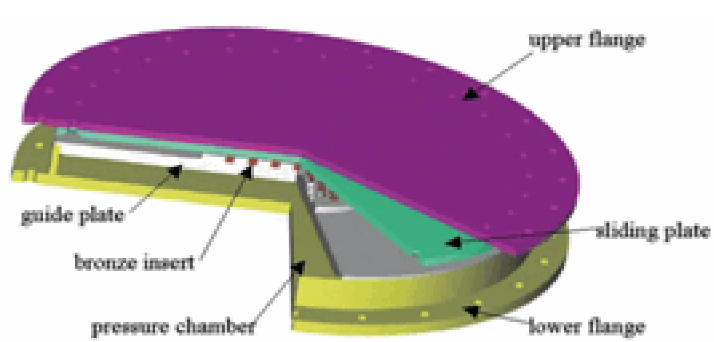


Fig. 10 – Elevated bridge with natural link to control and limit the forces on the piers (Hyde-system approach and semi-active friction device UHYDE-*fbr* (patented) suitable for this purpose [6].

Conventional structural concepts do not provide this robustness. New concepts need to be introduced into mainstream bridge building, especially for deck bridges (Fig.10). Seismic control concepts, especially rigid body motion control in its passive or semi-active form introduced into deck bridges as Hyde-system [6] not only provides robustness under earthquakes but also reduces construction costs and can be used easily to retrofit most existing deck bridges.

To avoid floating-off of decks during a tsunami, sufficient holes must be provided for the air to escape. Scouring around piers must be limited to acceptable damage levels. This may require additional protective measures also up-stream against the debris-filled back-flow. Where debris may accumulate against a bridge, the bearing situation may have to be altered to prevent drop-off of sections. Simple additional measures like horizontal stoppers on piers and abutments may suffice in such cases. These measures need further investigations including wave tank simulations on models where tsunami waves can be generated.

Many piers and abutments are able to sustain smaller earth movements that result from landslides without the kind of displacements that cause section drop-offs, but this is not very well understood and needs further studies (numerical and experimental). Where landslides may occur and endanger a bridge, standard preventive measures can be taken that stabilize the slopes or rock faces in question. Additional measures may be necessary in areas where, due to the extreme nature of the event, more massive slides may occur or where no slides are expected so far. In some mountainous regions, that may lead to a re-design of the entire road including extensive tunneling and rock avalanche protection.

If a fire is allowed to burn out of control, especially if it is underneath a bridge, it has the capacity to destroy this bridge, especially after an extreme earthquake when such fires may be wide spread and can burn for hours. Appropriate passive measures such as extra fire coating may be applied to a single, high impact bridge, but are too expensive to apply to elevated roads in general. High-impact bridges may even require permanent fire extinguishing systems on site in order to allow their immediate use, especially for tsunami evacuation.

More studies are needed beginning with realistic fire scenarios under such circumstances to understand the impact of fire on residual functionality more clearly. Then, economically reasonable measures to prevent zero functionality may come within reach.

5. Rapid Assessment and Repair

A robustness based retrofit of a road network may not be completed when the extreme event occurs. Thus, rapid damage assessment methods are needed to assess the residual functionality. This is typically based on "expert opinion" and a web-based tool has been developed for this purpose some time ago [7]. It can contain all major damage patterns discussed before. Expert opinion usually provides a rather conservative estimate and may not be available fast enough. This is illustrated by an incident that happened during rescue operations following the Kobe earthquake. A military commander asked an official of the road network operator whether it was safe for his unit to cross a damaged bridge. The official could not answer this question. A volunteer was sent across. Fortunately, the bridge had enough emergency functionality left and the unit could proceed safely.

To allow rescue and especially evacuation to proceed with the necessary speed (the Osaka scenario only allows for 30 min before the arrival of the tsunami in Minato Ward!), More realistic estimates of residual functionality are needed almost immediately. This can be achieved through a web-accessible database, which contains the before-mentioned damage states, but in direct relation to particular bridges and their components in the network.

A realistic pre-estimate of the remaining load bearing capacity of bridge components subjected to various levels of damage can be performed as a basis to realistically assess residual functionality. This was illustrated in a study performed in ROADERS where a typical punch-through failure of the bottom girder due to unseating was assumed for an old steel bridge (Fig.11) [8]. Using a simple local plastic hinge model with a reduced plastic moment capacity $M_{pl,red}$ for the damaged box section, it was easily confirmed that a 7 ton emergency truck can pass the bridge safely, even if the remaining $M_{pl,red}$ is only 10% of the original M_{pl}.

This rather crude study already indicated that 100% emergency functionality may be commonly available under such circumstances. Local FE-models of such damage zones can further improve such a pre-assessment, but should be also validated experimentally. Doing such studies will provide realistic capacities for each bridge in a network under various observable damage states and this information will be available immediately on site through improved emergency management tools like the “Intelligent Disaster Decision Support System“ (IDDSS) [9], which was recently developed to provide a platform for integrating a vast range of road network, traffic, geographic, economic and meteorological data as well as dynamic disaster and transport models. Thus, realistic data with respect to residual functionality can enter agent-based evacuation studies almost immediately, making them more reliable and quickly adaptable to the situation at hand.

Hanshin Expressway Earthquake Museum

Case study: unseating of Siret River Bridge, Romania

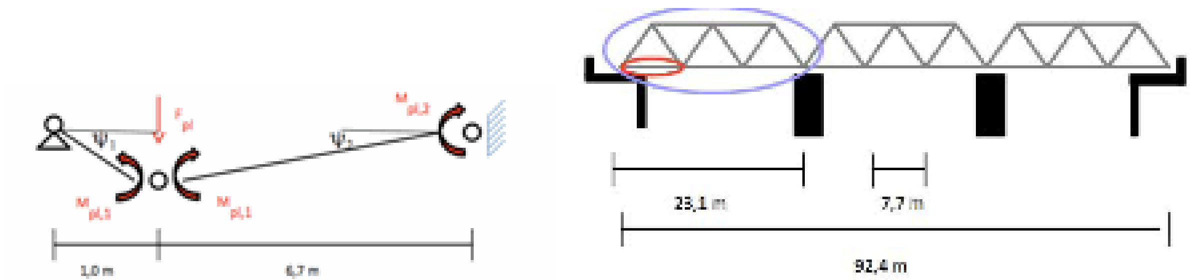


Fig. 11 – Typical punch-through failure due to unseating of a steel bridge (upper left) and a simple estimation of residual load bearing capacity for an old steel bridge, still providing 100 % emergency functionality [8].

Other failure patterns are less forgiving. This is particularly true for shear cracks in piers (Fig.5 left). In such cases, it may be difficult to assess the residual bearing capacity without closer inspection and immediate emergency level repair may be the better option. This could be done for example with an adaptable steel tie system, that can be held in stock and applied quickly without the need for heavy equipment (Fig. 12) [10].

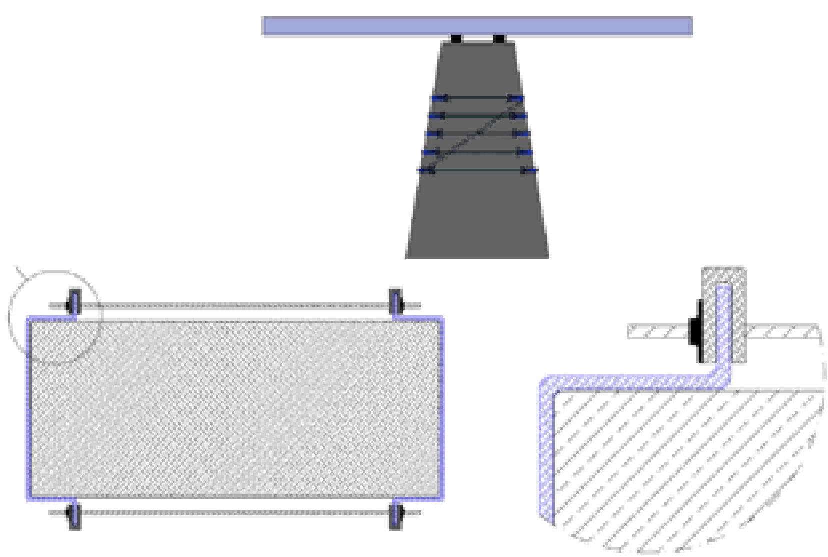


Fig. 12 – Adaptable steel-tie system for rapid emergency repair of concrete piers that have failed in shear [10].

6. Conclusions

A combination of traffic management tools is able to identify bridges that are critical for emergency response and evacuation after an extreme earthquake event. They need realistic estimates of residual emergency functionality, which is a function of the remaining load bearing capacity. Such events trigger multiple hazards (liquefaction, fires, land slides, tsunami) that depend on the location of a bridge. Damage to bridges due to such an event sequel is poorly understood and further research (numerical and experimental) is needed here. ROADERS provided a first framework for this, especially with respect to the "robustness" of bridges. It requires a bridge design that secures a minimal functionality beyond its regular safety-based design limit.

Because of this definition of robustness, certain damage states must be avoided where others can be tolerated. Conventional structural systems often cannot provide this. Seismic Control, especially in the form of the Hyde-System is capable of avoiding often-observed failures that lead to zero functionality, like piers failing in shear. With its proven economy, it is therefore an excellent alternative, especially for deck bridges.

Where such shear failure does occur, a rapid repair system is suggested that can be applied quickly and without the need for heavy equipment.

Pre-disaster structural studies must be performed and validated for various levels of damage states in order to obtain a realistic picture of a bridge's remaining functionality. This information can then enter advanced and dynamic disaster management systems (like IDDSS) to allow realistic agent-based simulations for well-informed decision making within minutes.

This may be required especially for emergency evacuation when, like for Osaka, only 30 minutes are available before the tsunami arrives.

6. References

[1] Japan Cabinet Office (2012). Nankai Trough earthquake damage information. Available from: <*http://www.bousai.go.jp/jishin/nankai/nankaitrough_info.html*>. [1 October 2013].

[2] Osaka Prefecture Office, (2013). Osaka Prefecture emergency road network. Available from: <*http://www.pref.osaka.jp/attach/9128/00000000/zu.pdf*>. [1 Oct 2013].

[3] J.S.E. Teo, J-D. Schmöcker, F. Leon, J.Y-T. Li, H. Yamazaki, A.G. Qureshi, G.M. Atanasiu, E. Taniguchi (2015): Evaluating disaster network resilience with an agent-based evacuation model, *4th ROADERS Workshop,* Sapporo, Japan, 1-25.

[4] F. Leon, G.M. Atanasiu, A. Constandache (2014): Agent-based modeling framework for post-disaster evacuation analysis in Iasi, Romania, *2nd ROADERS Workshop,* Kyoto, Japan, 20-40.

[5] U.E. Dorka (2014): Robustness of bridges under multiple extreme events, *2nd ROADERS Workshop,* Kyoto, Japan, 41-47.

[6] U.E. Dorka, (2014): Seismic control for elevated roads, *Building Materials And Structures* **57** (4), 9-20.

[7] J.E. Padgett, R. DesRoches (2007): Bridge functionality relationships for improved seismic risk assessment of transportation networks, *Earthquake Spectra* **23** (1), 115-130.

[8] F. Obón, U.E. Dorka (2014): Preliminary studies on the rail road steel bridge visited during the workshop in Romania, *2nd ROADERS Workshop,* Kyoto, Japan, pp. 55-59.

[9] A. Rajabifard, R.G. Thompson, Y. Chen (2014): A decision support system for improving the management of traffic networks during disasters, *3rd ROADERS Workshop,* Kassel, Germany, 27-34.

[10] A. Mühlhausen, U.E. Dorka (2014): Preliminary studies of quick repair and recovery methods for bridges, *3rd ROADERS Workshop,* Kassel, Germany, 35-41.