A Global Methodology for Seismic Vulnerability Assessment and Retrofit of Existing Bridges adapted to the French Context

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SUMMARY:
Initiated in 1997 under the supervision of the Directorate of Roads of the French Ministry of Public Works and Transportations, the SISMOA method was created in order to provide a qualitative estimation of the seismic vulnerability of existing bridges, based on geometrical and typological criteria. By combining vulnerability, hazard indices and bridge strategic importance, the approach enables to determinate which bridges should be more precisely analyzed and eventually retrofitted in priority. Since 2006, a task-group gathering many actors of the French road community, including State organizations, highway companies and structural engineering offices, has been working on the second step of the methodology. The purpose is to define specific seismic assessment methods, retrofitting appropriate techniques as well as performance/cost optimum risk reduction objectives. The approach has already been tested on several operational studies in the south of France. Each of them enabled to check and better calibrate the method.

Keywords: Bridges, assessment, retrofit, prioritization scheme, performance/cost optimum

1. INTRODUCTION

Scientific advances and design codes evolutions in the field of earthquake engineering raise the question of the level of resistance of older structures to seismic actions. In France, the first set of moderns seismic design codes is known as PS92 and was published in 1995. In 2002, a State requirement relative to seismic risk prevention was established to encourage strategic equipment (such as civil infrastructures and public buildings) owners to proceed to structural seismic assessment and retrofit if needed. However, contrary to new structures, no specific guidelines is available for existing structures.

This paper aims to present the global methodology that has been developed since 2006 in France for seismic vulnerability assessment and retrofit of existing bridges. This methodology will soon be published by Sétra (the engineering office in charge of roads and bridges within the French Ministry of Sustainable Development). It has been established by a task-group gathering many actors of the French road community, including State organizations, highway companies and structural engineering offices, and was inspired from analogue studies developed in other countries like California [Priestley, M.J.N et al., 1996], Japan [Légeron, F, 2001], Italy [PIARC C4.4, 2007] and Switzerland [OFROU, 2005]. The objective is to adapt those different approaches to the French context in terms of bridges typologies and characteristics, moderate seismic activity region and economical issues. The guidelines will be addressed to infrastructure owners, local civil authorities in charge of bridges maintenance for what concerns decisional aspects as well as structural engineering offices and construction companies for technical aspects. Those guidelines aim to cover critical issues such as:

- Which bridges to treat in priority?
- What kind of analysis methods to use for seismic vulnerability assessment?
- What level of performance to reach through seismic retrofit? And at which cost?

2. PRIORITISATION SCHEME

The first step of the methodology consists in defining which bridges should be more precisely investigated, analyzed and eventually retrofitted among a large number of structures. This prioritization scheme is based on three criteria (see Fig. 2.1):

- The expected seismic activity and potential induced phenomena at the location of the bridge,
- The structure roughly evaluated vulnerability,
- The social/economical importance of the bridge.

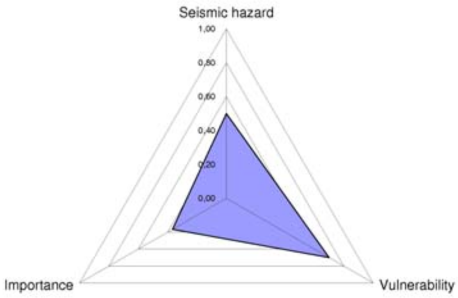

Figure 2.1. Prioritization scheme for bridge seismic assessment and retrofit

2.1. Seismic hazard characterization

The expected seismic hazard at the location of the bridge includes soil vibration, in terms of nominal acceleration and site effects, as well as induced phenomena, such as liquefaction, rock fallings and landslides.

2.1.1. Reference seismic action

The reference seismic action (A_{Ek}) is based on the new French seismic hazard map that was published in 2005 by the French Ministry of Sustainable Development (see Fig. 2.2).

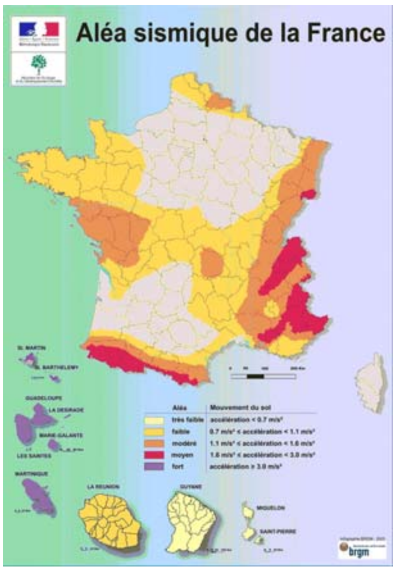

Figure 2.2. French seismic hazard map published in 2005

According to this map, the French Territory including Caribbean and Indian Islands, is divided into five different seismic zones, so-called very low, low, moderate, medium and strong seismic activity regions. The associated recommended reference acceleration values are given in Table 2.1.

Table 2.1. Recommended reference accelerations for the five French seismic zones

Seismic zone	Seismic activity	A_{Ek}
Z1	Very low	0 m/s^2
Z2	Low	0.7 m/s^2
Z3	Moderate	1.1 m/s^2
Z4	Medium	1.6 m/s^2
Z5	Strong	3.0 m/s^2

2.1.2. Site effects

Site effects include both geological and topological seismic waves amplifications. Those effects are taken into account through two coefficients, S and τ respectively. S factor is consistent with Eurocode 8 soil categories and coefficients (see Tab. 2.2). The τ coefficient varies in the range 1.0 to 1.4 depending on site topography and relief conditions.

Table 2.2. Soil coefficient S for different EC8 soil categories

Soil categories	S (Z1 to Z4)	S (Z5)
A	1	1
B	1.35	1.2
C	1.5	1.15
D	1.6	1.35
E	1.8	1.4

Finally, the seismic hazard A_{vib} related to seismic vibration is given by Eqn. 2.1 below:

$$A_{vib} = A_{Ek} \times S \times \tau \qquad (2.1)$$

2.1.3. Induced phenomena

The analysis includes the evaluation of seismic induced phenomena such as liquefaction, rock fallings and landslides. At the first step of the methodology, the purpose is to get a first evaluation of the susceptibility for those phenomena to happen under the reference seismic action. Therefore the evaluation is mainly based on simple qualitative and typological easy to access parameters such as soil properties (depot age, water saturation level, soil density and cohesion…), slope angles, geomorphology, blocs sizes and stability, vegetation density and eventual existing protections (nailing, wires…) [Duval, A.M et al., 2006].

2.2. Seismic vulnerability evaluation

Since 1997, a specific tool called SISMOA has been developed in France to provide a first evaluation of the vulnerability of existing bridges, based on geometrical and typological criteria [Marchand, P et al., 2006]. This qualitative method was established from the observation and interpretation of damages caused by past earthquakes on bridges that enabled to identify a certain number of recurrent weaknesses due to design and constructions defects.

The SISMOA method results in a global grade V_{vib}, in the range $0 \leq V_{vib} \leq 1$, computed as a combination of specific vulnerability indices associated to the different parts of bridge: deck, abutments, columns and foundations (see Fig. 2.3). General parameters such as the bridge structure type (single span, multi-span, culverts, portal frames, masonry arches…), year of construction, design code and structure health are also taken into account.

Three additional grades, V_{liq}, $V_{landslide}$ and $V_{rock\ fall}$ are also computed, that aim to evaluate vulnerabilities to liquefaction, landslide and rock falls respectively.

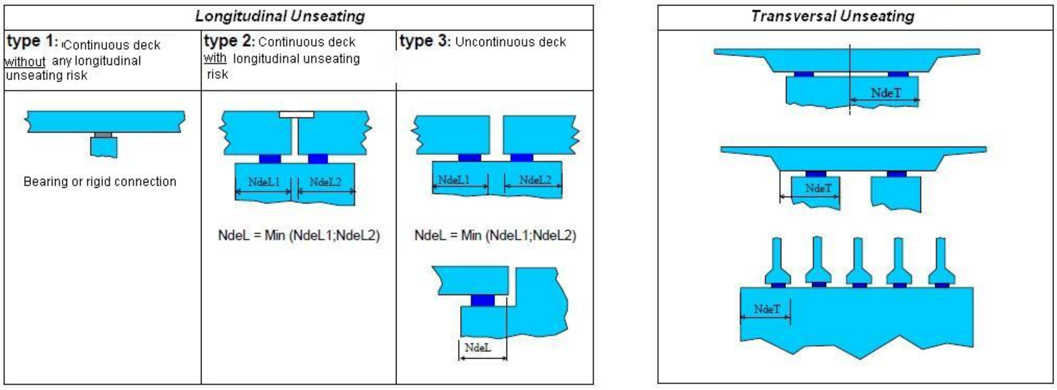

Figure 2.3. Evaluation of deck unseating potential vulnerability in SISMOA method

2.3. Bridges importance

A global matrix has been defined to evaluate bridges strategic importance in terms a short term crisis management (emergency issues) as well as long term social and economical activities. Many parameters are taken into account that concern the bridge structure itself but also the carried and crossed roads: potential of direct human victims in case of bridge collapse, strategic access to critical facilities like hospitals, airport or fire-fighters stations, available alternative routes, number of lanes, average traffic, local economy role, intrinsic value of the structure…

Finally, the fulfilled matrix gives a global importance grade called I, with I values in the range of 0 to 150, where short term aspects count twice as much as long terms criteria. Bridges with I values in the range of 0 to 50 are related to Eurocode 8 importance class I (less than average importance), I values in the range of 50 to 100 are related to class II (average importance) I values between 100 to 150 are related to class III (critical importance).

2.4. Selection of the bridges that need more precise investigations

2.4.1. Seismic risk evaluation

The seismic risk R_{vib} associated with seismic vibration is given by Eqn. 2.2. It is computed by combining seismic hazard A_{vib} with evaluated structure vulnerability V_{vib}. This relation has been calibrated through more sophisticated numerical analysis performed on a set of specific bridges.

$$0 \le R_{vib} = 0.703 \cdot Ln\left(\frac{A_{vib}}{4.51 \cdot e^{(-2.28\times V_{vib})}}\right) + 0.5057 \le 1 \qquad (2.2)$$

Seismic risks related to liquefaction hazard, landslides and rock fall, respectively called R_{liq}, $R_{landslides}$ and $R_{rock\ fall}$, are expressed on the same format. The global risk grade R is defined as the maximum of R_{vib}, R_{liq}, $R_{landslides}$ and $R_{rock\ fall}$.

2.4.2. Bridges selection

The proposed methodology recommends to proceed to more precise investigations for all bridges verifying $R \times I \ge 50$. Those additional investigations include in-site geotechnical and structural investigations as well as numerical analysis.

This selection implicitly excludes from the second step of the analysis bridges of importance class I (less than average). More generally, the procedure aims to precisely analyse and retrofit in priority bridges potentially highly vulnerable, located in zones of moderate to strong seismicity and of critical importance.

3. DEFINITION OF AN ACCEPTABLE LEVEL OF PERFORMANCE

3.1. Performance criteria

The performance indices α_{conf} of a selected bridge is expressed by Eqn. 3.1 as the ratio between the maximum ground acceleration $A_{max\ adm}$ it is able to resist and the design acceleration A_{Ed} it should be designed for if it was a new structure.

$$\alpha_{conf} = \frac{A_{max\_adm}}{A_{Ed}} \tag{3.1}$$

Where $A_{Ed} = \gamma_I .A_{Ek}$, with γ_I=1.0 for importance class I, γ_I =1.2 for importance class II and γ_I =1.4 for importance class III.

Based on Eurocode 8-3 principles, three different Limit-States are defined for this evaluation, that can be plotted on a conventional push-over curve as presented on Fig 3.1:

- Limit State of Damage Limitation (DL),
- Limit State of Significant Damage (SD),
- Limit State of Near Collapse (NC).

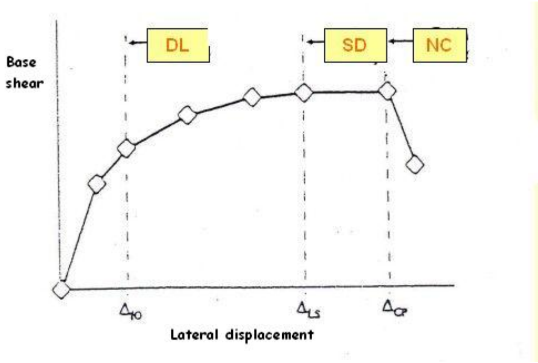

Figure 3.1. Limit States for seismic performance evaluation according to EC8-3

3.2. “Best optimum” performance requirement objectives

The level of performance that can be considered as acceptable for an existing bridge without any retrofit is defined as a function of the evaluated remaining service life (see Fig. 3.2). This performance curve also helps to define the level of performance to reach through retrofitting for a bridge that has shown to exhibit unacceptable level of seismic risk.

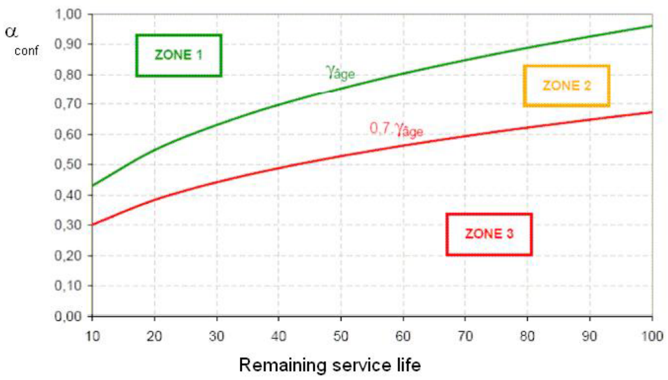

Figure 3.2. Recommended performance requirement objectives

On this figure, zones 1, 2 and 3 are defined as follows:

- Zone 1: Acceptable risk (no retrofit needed for the existing structure);
- Zone 2: Risk to reduced to an optimum performance/cost level depending on available means;
- Zone 3: Unacceptable risk (retrofit strongly recommended).

4. RECOMMANDED METHODS FOR STRUCTURAL ANALYSIS

4.1. Choice of the most appropriate analysis method

The proposed approach and guidelines provide a full description of available analysis method for seismic vulnerability assessment of bridges structures, including conventional force-based analysis, monomodal and multimodal spectral analysis, displacement-based and push-over analysis, and nonlinear time-history analysis… The choice between those different methods is established by considering structural typology and regularity, direction of seismic load, design and in-situ investigations data (including dynamic response investigations). They are adapted to existing structure assessment objectives which consist in precise evaluation of structural behaviour and resisting capacities. Soil/structure interaction [Dobry, R et al., 1982], [Gazetas, G, 1983], [Fin, W.D.L, 2005] and bad detailing in terms of concrete confinement, reinforcing steel anchoring and lap splice [Xiao, Y et al., 1997] and anti-bucking dispositions [Gomes, A, 1997] are also taken into account

4.2. Displacement based assessment and push-over analysis

It has to be noted that displacement-based and push-over analysis are particularly well adapted to seismic vulnerability assessment. In particular, they enable to describe the full chronology of structural damage under increasing seismic loading (see Fig. 4.1), taking into account structure redundancy and load redistribution possibilities. Moreover the resulting push-over curves make quite easy to evaluate and check the Limit-States defined in 3.1.

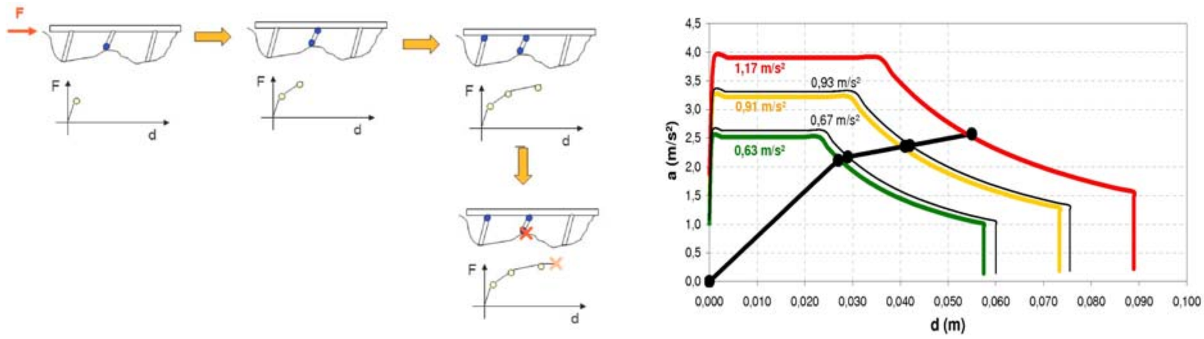

Figure 4.1. Push-over analysis adapted to existing bridge structure assessment

5. SEISMIC RETROFIT

5.1. Retrofitting strategies

Different retrofitting strategies are proposed in the approach that are chosen to fit common French bridges typologies. Those strategies (see Fig. 5.1) include structural softening (for instance by modifying elastomeric bearings characteristics), improvement of column ductility, reinforcement of weak elements (column or foundations), or increasing structural damping through additional external dampers…

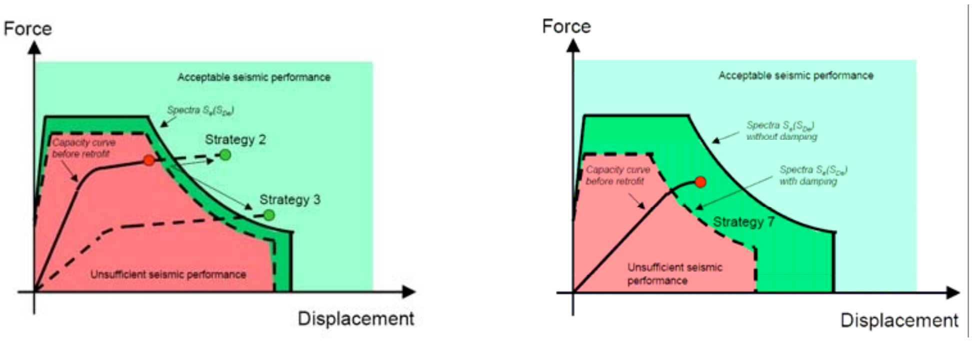

Figure 5.1. Examples of retrofitting strategies

5.2. Multi-criteria comparison of different possible retrofit solutions

The choice of the "best" retrofit solution among all possible strategies must be established using a multi-criteria comparison approach. The criteria for this comparison should include maximum admissible acceleration gain ($\Delta_{Amax\ adm}$), achieved seismic performance α_{conf}, retrofit cost, technical feasibility, reliability, service compatibility, maintenance issues and post-seismic interventions.

It is recommended that this multi-criteria analysis includes at least two "extreme" solutions that correspond respectively to "no intervention" solution (zero performance gain at zero cost) and a demolition/reconstruction solution.

6. EXAMPLES OF OPERATIONAL APPLICATIONS IN THE SOUTH OF FRANCE

6.1. Global evaluation of the seismic vulnerability of highways infrastructures in Provence area

The whole methodology has been tested and calibrated, in terms of global induced cost, on a set of highways infrastructures in Provence area, mainly composed of small regular bridges (see Fig. 6.1).

Figure 6.1. Global evaluation of the seismic vulnerability of highways infrastructures in Provence area

Among the 63 tested bridges, 4 have been identified as needing more sophisticated numerical analysis, that mainly correspond to highway carrying bridges and multi-highways crossings. Those analysis have shown that the seismic risk associated to those bridges could be significantly lowered by some simple interventions such as elastomeric bearings replacement, seismic blockers and local column reinforcement, with an associated cost less than 5% of the replacing cost of the structure.

6.2. Seismic assessment and retrofit project of five Viaducts near Perpignan

The methodology has also been used for an operational project consisting in seismic assessment and retrofit study of five viaducts built in the 70's near Perpignan on highway A9 close to Spanish border (see Fig. 6.2). For those five quite similar viaducts, the adopted retrofit strategies consist in abutments anchorage, elastomeric bearings replacement, multi-span rigid restrainers and installation of additional external seismic dampers, in order to reduce both seismic forces and displacements in the structure. The reached performance indices are close to 100%, with associated costs between 2% and 13% of the replacing costs of the bridges.

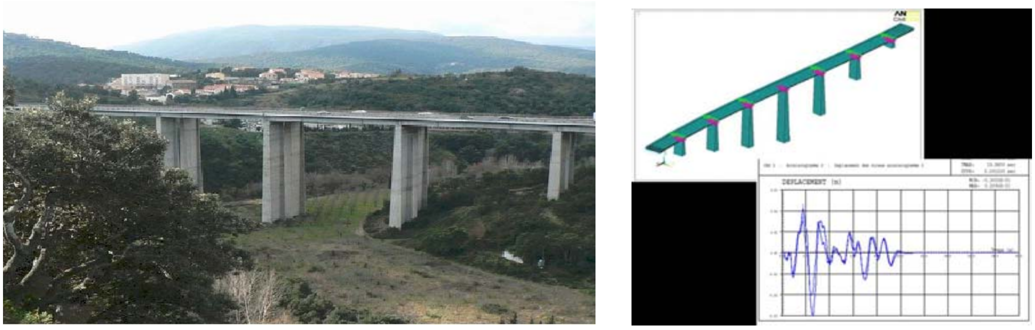

Figure 6.2. Seismic assessment and retrofit project of five Viaducts near Perpignan

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