Bollettino di Geofisica Teorica ed Applicata Vol. 54, n. 3, pp. 205-215; September 2013
DOI 10.4430/bgta0076

Rapid instrumental check of vulnerability parameters on bridges for seismic risk mitigation purposes

S. Grimaz[1], P. Malisan[1], F. Barazza[1] and R. Carniel[2]

[1] *Laboratorio di Sismologia Applicata, Dipartimento di Chimica, Fisica e Ambiente, Università degli Studi di Udine, Italy*
[2] *Laboratorio di Misure e Trattamento dei Segnali, Dipartimento di Ingegneria Civile e Architettura, Università degli Studi di Udine, Italy*

(Received: February 14, 2011; accepted: July 20, 2012)

ABSTRACT In recent years, Italian legislator has underlined the necessity of a seismic risk evaluation for relevant and strategic buildings, in order to define proper strategies for seismic risk mitigation. Most of the bridges should be considered as strategic structures for the importance of guaranteeing road connections, and therefore it is necessary to estimate the potential consequences in case of an earthquake. If a large amount of structures is involved, it is preferable to adopt an approach that permits a rapid check of some significant vulnerability parameters, both for sites and structures. In this paper, an ambient tremor measurement approach (PICOS-Vul method) is illustrated and it is shown how the method can be used for a direct and rapid characterization of some vulnerability parameters that represent the dynamical behaviour of each structure.

Key words: seismic risk, vulnerability, bridges, NE Italy.

1. Introduction

Italian seismic legislation underlines the importance of checking relevant and strategic structures in order to estimate their seismic risk, considering hazard, vulnerability and exposed value evaluations. For seismic risk mitigation purposes at a territorial level, it is necessary to estimate and compare some vulnerability parameters that represent the dynamical behaviour of the structures; furthermore it is necessary also to consider the hazard level and the local response of the sites. Consequently, it is fundamental to find methods that permit to quickly and cheaply check the vulnerability parameters and that give an indication of the significance of the ground-structure dynamical interaction.

Bridges are generally considered strategic structures, because of the importance of guaranteeing road connections (especially after natural disasters); many studies have developed different approaches for their vulnerability assessment. Usually, bridge vulnerability evaluations are based on the use of fragility curves (see: Mander, 1999; Franchetti *et al*., 2008; Onida *et al*., 2011); this implies that the results are the outcome of an indirect estimation procedure rather than a direct measurement on the structure. Nevertheless, a direct approach to vulnerability analysis of structures could be derived from methods proposed for other structural typologies. Nato SfP project [Assessment of seismic site amplification and seismic building vulnerability in Former Yugoslav Republic of Macedonia, Croatia and Slovenia; Mucciarelli (2010)] and

ASSESS project [Analysis of the seismic scenarios of the school buildings for a definition of retrofitting priorities for seismic risk reduction, in Friuli Venezia Giulia; Grimaz *et al.* (2011a, 2011b)] proposed the application of an instrumental check method, based on ambient tremor measurements, for the rapid evaluation of some vulnerability parameters on a large number of buildings. The approach should be considered particularly significant for checking vulnerability parameters for risk reduction purposes: it is cheap, rapid, direct and it permits also to evaluate site effects (and therefore to consider the behaviour of whole site plus structure scenario).

This passive instrumental method can be applied also to bridges. This paper presents a short review of the approaches commonly used for evaluating vulnerability of constructions, and the proposal of a direct method for checking some significant vulnerability parameters on bridges. Furthermore, two applications of the method are illustrated, the first focused on the comparison between the results of the passive instrumental approach with other direct methods, and the second aimed to verify the rapid characterization of vulnerability. Finally, comments on the method and the limitations of its applicability and of the validity of the results are presented.

2. Seismic vulnerability assessment at a regional scale

There are several methods that can be used in order to estimate vulnerability parameters for constructions at a regional scale. It is possible to differentiate them on the base of the typology of analysis, that can be empirical, numerical or instrumental. Furthermore, it is possible to distinguish between indirect or direct approaches, if the results depend either on statistical or empirical data (indirect), or on measures and inspections on the structure (direct).

Empirical methods are usually based on statistical interpretations and can be applied after fairly rapid surveys on the structures (that generally imply the compilation of specifics reports). The results indirectly describe the seismic behaviour of the structure and are based on the development and usage of fragility curves. These methods provide estimates at a territorial level, that cannot be used for defining specific intervention priorities. Furthermore, these methods do not give information on site characteristics.

Numerical simulation methods provide an estimation of the dynamical structural behaviour; in particular they calculate eigen-frequencies, eigen-modes and the maximum horizontal acceleration that the structure can withstand. The methodology requires, however, a precise knowledge of a lot of input data, such as the detailed geometry of the structure and the elastic-mechanical properties of the materials; for existing structures, these are usually known with large uncertainty, unless in-depth material tests have been performed. Furthermore, it is necessary to consider that numerical simulations require simplifying assumptions (for example on the constitutive law of the material, on the damping factors, on friction, etc.). Taking into account all the approximations, it comes out that the results will be affected by an uncertainty at least comparable to that of the input data. Moreover, numerical simulations require a high skilled staff. This makes these methods very expensive both in terms of cost and time and, therefore, prohibitive in practice for large-scale applications. Furthermore, the site evaluation is limited to the knowledge of the site class, as defined by NTC (2008) standards.

Instrumental methods applied to structures can be divided in two main categories, characterized by the excitation source (active or passive).

Active source instrumental methods excite the structure with a relatively high energetic external force, typically obtained with a frequency sweep using a vibrodyne. The structural behaviour is then measured with an appropriate deployment of accelerometers (see, for example, Morassi, 2008). The high-amplitude, narrow-band forcing permits to excite also the higher eigen-modes and, therefore, to discern them with precision. This methodology is reliable but its applications are usually expensive and time-consuming. Moreover, it is not always applicable because high energy excitations imply significant stresses on the structure and this could not be suitable for application on old or badly maintained constructions. Furthermore, even if the method gives objective results about the structural dynamical behaviour, it does not give any information about local site effects.

Passive source instrumental methods are based on the measurement of ambient noise, therefore the “every day” actions (micro-tremors, micro-seismic, man-made noise, wind, etc.) are used as forcing. Higher eigen-modes require higher energy in order to be excited. Therefore, due to low-amplitude, wide-band forcing, only the lower eigen-frequencies and eigen-modes can be detected, and the uncertainty in their estimation is generally greater than the one of active methods (see e.g., Timoshenko, 1937).

The knowledge of the eigen-modes, and overall of the eigen-frequencies permit to obtain useful information about some vulnerability parameters. In fact, the characterization of structural and ground frequencies permits to recognize the presence of double resonance effects that can cause a greater damage in the structure in case of seismic event.

Passive excitation methods also allow to assess the site local response, in terms of fundamental frequencies of the site [for example adopting HVSR method, see SESAME project; Bard (2008)] or to estimate the stratigraphy [ReMi®; Louie (2001)]. Furthermore, this method could be applied on structures at regional scale since it is rapid and cheap and provides objective performance indicators, measured with geophysical surveys.

3. Passive instrumental check of vulnerability parameters for bridges

Passive Instrumental Check of site-structure Scenario for the rapid characterization of Vulnerability parameters (PICS-Vul) method aims to identify seismic critical behaviour by analysing the tremor recorded on the structure and on the site in the neighbourhood. In fact, an evaluation of the possibility that future earthquakes could damage a building has to consider the seismic behaviour both of the structure and of the site with an overall view. In the following the ensemble of site and structure will be called “scenario” (Fig. 1).

The ambient noise measurements are carried out using seismometers with 3 orthogonal components (in our case a Lennartz LE 3Dlite-1s seismometer and a Lennartz M24 compact LP digitizer were used).

The behaviour of the site is investigated by the HVSR technique, that permits to define:

- the presence of a significant impedance contrast (that may cause an increment of the seismic action on the ground surface);
- the natural frequency(ies) of the ground;
- the presence of lateral variability of the site layers.

The behaviour of the structure is investigated using SSR (Standard Spectral Ratio) method;

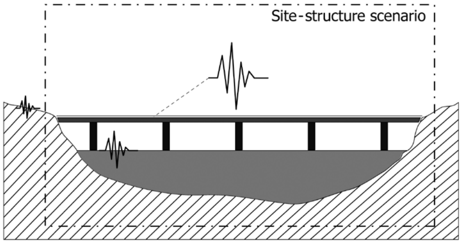


Fig. 1 - Site-structure scenario. For an adequate evaluation of the tendency to a seismic damage of a structure, the seismic behaviour both of structure and site has to be considered.

the technique permits to estimate the transfer function of a construction, after computing the tremor spectral ratios of structure and site. The determination of peaks in the transfer function reveals then the natural frequencies and the relative amplifications. The joined analysis of tremor measurements on structure and on site permits to define:

- the low-order eigen-frequencies of the structure;
- the relative eigen-modes;
- the possible presence of soil-structure resonance (double resonance effect).

The knowledge of the natural frequencies of a structure is essential in order to constrain the numerical analyses. Usually, finite elements models present essential simplifications and the comparison with the real behaviour permits to establish the representativeness of a model (and/or to indicate corrections).

The HVSR curve permits instead to define some characteristics of the site and therefore to point the attention on specific and useful geophysical analyses (if needed); in fact the possibility to distinguish between 1D or 2D profiles and to identify the global behaviour of the site permits to choose the optimal site geophysical analyses in order to obtain deeper and more accurate results (for example with MASW analyses).

Finally, the comparison of site and structure frequencies (in particular of the fundamental frequency) permits to identify the presence of possible double-resonance effects that will magnify the seismic action on the structure.

4. Survey design

The measurement surveys need to be accurately designed in order to obtain meaningful parameters and repeatability. Firstly, it is necessary to recognise the “structural unit” to be evaluated: the presence of seismic joints or other structural discontinuities implies the existence of more structural unities and the analyses should be performed for each of them. When a structural unit has been identified, seismometers should be placed in order to measure the maximum displacements and, as a consequence, to minimise the relative errors. It is necessary, therefore, to assess the behaviour of the structure in order to avoid placing the seismometers in correspondence of the eigen-mode nodes, where the displacements are negligible. The number of the measures depends on the expected results: the evaluation of the fundamental frequencies needs only one or two measures on the structure, while the measurement of the eigen-modes implies the need for more measurement points depending on the characteristics of the construction. The seismometers should be placed far away from secondary elements of the structure that may have proper natural frequencies and that can, therefore, affect the data (for example parapets, etc.). Tests show that the vehicle traffic on bridges does not influence the results of the analysis, but the transfer function does not give any information on amplification factor. The measurements do not need, in general, to be simultaneous; however, simultaneity permits to compare the phase spectra and then to easily identify the eigen-modes.

The position of the measurement point on the ground should satisfy some conditions: firstly, it should permit to characterise the site behaviour; secondly, it is important to avoid as much as possible, noise record of other structures or elements, like trees, traffic or other man-made localised noise. The nearness to the construction is also a parameter to be taken into account: measurements too close to the structure may record its natural frequencies and therefore SSR may provide lower amplitude values.

5. Applications of the PICS-Vul method to bridges

The PICS-Vul method has been applied to two bridges in north-eastern Italy (Salt and Silea bridges). The two bridges are quite similar, despite some differences in the structural components: they mainly consist of a reinforced concrete deck over piles of constant height. Specific characteristics and information on the two bridges are reported in the next paragraphs.

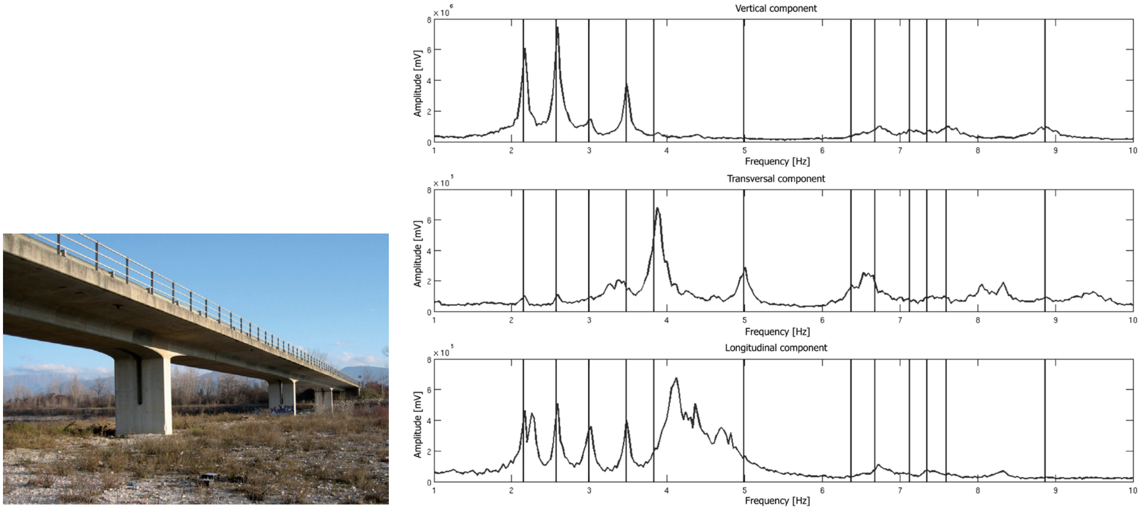
5.1. Salt bridge

The proposed approach for checking vulnerability parameters has been applied to the Salt bridge (Fig. 2a) during a project aimed to the study of some bridges in the province of Udine (north-eastern Italy).

The Salt bridge consists in a pre stressed concrete “beam” with 7 spans. The deck has a thickness of about 1.0 m and a width of 10.0 m. The five central spans have a length of 36.0 m, the lateral ones of 25.5 m. The piers are made by reinforced concrete and have a thickness of 0.9 m; the foundation of each pier and of the abutments are realised by two concrete piles with diameter of 1.8 m and length of 14.3 m. Seismic devices are present in correspondence of the supports of the deck on the first and on the last piers. The other piers are embedded with the structure. The thermal dilatation joints are localised on the two abutments.

The Salt bridge has been studied with active excitation (vibrodyne) and numerical methods (Morassi, 2008). In addition, also passive tremor measurements have been performed on several points of the structure (Grimaz and Riuscetti, 2008; Malisan *et al.*, 2008). The comparison between the methods has shown good congruence of the results. Fig. 2b shows the correspondence between the fundamental frequencies identified with the vibrodyne (vertical lines) and the mean spectra measured with passive method, along the three main directions of the bridge (vertical, transversal and longitudinal). The two methods provide almost the same results; in particular, in this case, the fundamental mode and the three over-modes for each orthogonal component are identified.

The site has been analysed with three HVSR measurements. Furthermore, two ReMi®, MASW and refraction surveys have been carried out, in order to estimate the values of V_S of the first ground layers and to define a simplified numerical model for the site. The HVSR curves show a peak at circa 16-18 Hz, that represents an impedance contrast ratio corresponding to a very superficial layer. Considering the shallowness of the first layer and the depth of the piles



(a) (b)

Fig. 2 - Salt bridge: a) photo of the bridge; b) comparison between active and passive method results. Vertical lines identify the fundamental frequencies found with vibrodyne method. Thick line curve is the mean value of the tremor measurement spectra on the bridge.

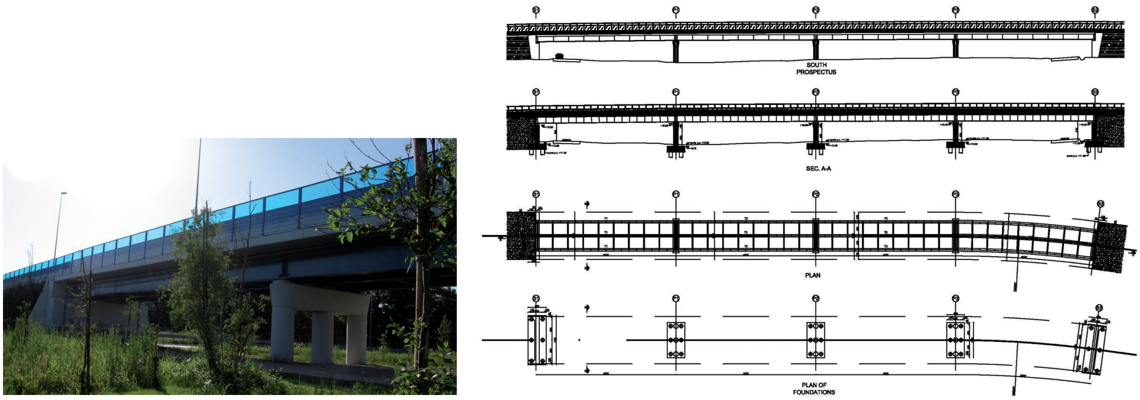
under the ground, also a numerical simulation of the site effects has been performed, in order to verify the site effects at the foundation depth. The analyses, carried out with a ground model built with SHAKE 91 (Schnabel *et al.*, 1972), show that the ground could amplify the site frequencies around 4-5 Hz (see Grimaz and Riuscetti, 2008). The transversal seismic behaviour of the bridge has the first fundamental frequency close to the theoretical site frequency, so we can assume that a certain degree of resonance between the structure and the ground at this frequency could arise.

The good comparison of the results of active and passive geophysical methods points out that passive excitation approach can provide reliable data for the evaluation of some vulnerability parameters (both for structure and site).

5.2. Silea bridge

The second case study concerns the Silea (small town in north-eastern Italy) bridge (Fig. 3). The bridge, a steel-concrete structure, has four spans each of about 40 m length; it is characterised by continuous S355 steel beams and a Rck40 concrete slab of thickness of 30 cm; steel beams and concrete slab are connected by Nelson pegs with diameter of 19 mm and height of 200 mm. Each pier has three columns of circular cross section with a diameter of 1.3 m. Foundations are reinforced concrete piles with a diameter of 1.0 m, length of 31.0 m underneath the lateral piers and 22.0 m underneath the central pier. The supports over the piers are seismic devices with transversely elasto-plastic behavior and longitudinal fluid-viscous behaviour.

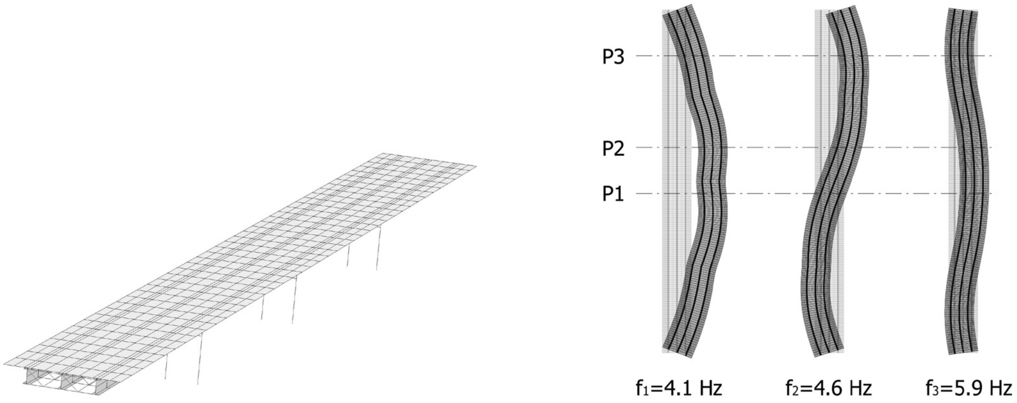
Three tremor measurements were carried out on top of the bridge and one on the site in close vicinity. During the measures, the construction was closed to traffic: this permitted to place the seismometers in the middle of the bridge. The three component seismometers were orientated with the S-N component parallel to the longitudinal axis of the bridge and, consequently, with the E-W component transversal to the axis.



(a) (b)

Fig. 3 - Silea bridge: a) photo of the bridge; b) sketch of the bridge.

In order to simply test the method, an essential FEM model (Fig. 4a) has been created, representing the transversal behaviour of the bridge. This permitted to compare the results of the numerical simulation with the measured transversal component of the structure. The analysis of the FEM transfer function indicates that the first transversal eigen-frequency is about 4.1 Hz and the second is 4.6 Hz. The lower eigen-frequencies and the eigen-mode provided by the FEM are shown in Fig. 4b.



(a) (b)

Fig. 4 - a) Finite element model of the bridge; b) representation of the three transversal lower eigen-modes and respective eigen-frequencies of the structure obtained by FEM. In the figure, the positions of the three measurement points P1, P2 and P3 are reported.

Fig. 5 shows the comparison between the transfer function for transverse motion computed by Standard Spectral Ratio (SSR) and by FEM analysis. Graphs show that there is a fairly good agreement among the first two measured eigen-frequencies and the ones of the numerical model. In particular, the second eigen-frequency it is not recognizable in the SSR of the point P1, as it is a node for the second eigen-mode (as reported also in Fig. 4b).

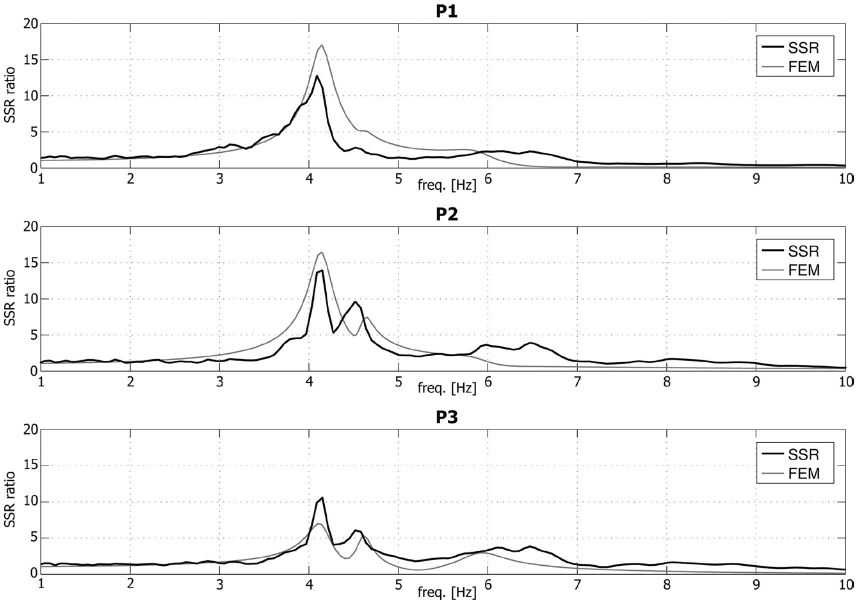


Fig. 5 - Comparison between the transversal transfer function obtained by geophysical methods (SSR) and numerical simulation (FEM) against frequency.

In order to study the site local response, the HVSR technique has been applied. The HVSR curve (Fig. 6) shows a broad peak between 3 and 7 Hz and a significant part with values of the ratio below the unity; this could be attributed to a velocity inversion (e.g., Castellaro and Mulargia, 2008) or an artificial water spring in the neighbourhoods that magnifies the vertical spectra in the range 10-20 Hz. In order to verify the results, a small campaign in the vicinities of the bridge has been conducted, and it showed that the HVSR curves are similar in the whole area. The comparison between the fundamental frequency of the site and the ones of the transversal behaviour of structure indicates the presence of a possible "soil-structure resonance", that could lead to greater damages in case of an earthquake.

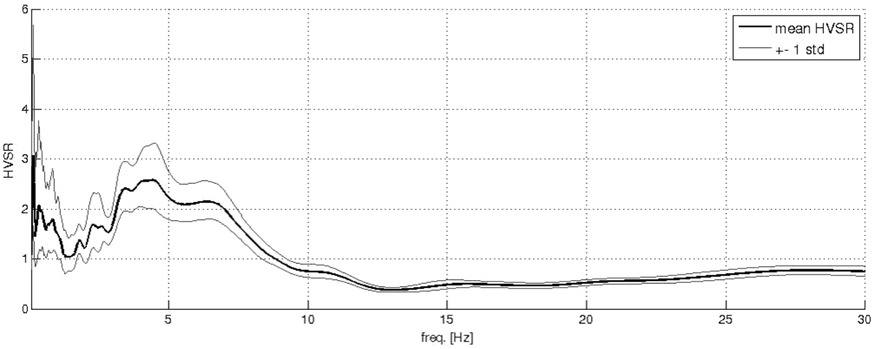


Fig. 6 - HVSR curve evaluated for the site in the neighbourhood of Silea bridge.

5.3. Summary of results for the case studies

The outcomes of Salt and Silea bridges lead to the definition of some data that concur to the evaluation of vulnerability parameters. The results are summarised in Table 1, in which the fundamental transversal frequencies of the two structures are reported as the outcome both of the measured cases and of the numerical simulations. Furthermore, the site fundamental frequency and an estimation of the potential double resonance effect are reported.

Table 1 - Comparison of the results obtained for Salt and Silea bridges. The first two fundamental transversal frequencies (*f1* and *f2*) are reported, both in the measured and in the numeric simulation cases (respectively “meas.” and “num.” in the superscript). The fundamental frequency of the site and the potential presence of double resonance effects are reported too.

Bridge	$f_1^{meas.}$	$f_1^{num.}$	% difference	$f_2^{meas.}$	$f_2^{num.}$	% difference	f_{site}	Pot. double resonance
Salt	3.9 Hz	3.8 Hz	2%	5.0 Hz	5.0 Hz	<1%	4-5 Hz	Yes
Silea	4.1 Hz	4.1 Hz	<1%	4.5 Hz	4.6 Hz	2%	3-7 Hz	Yes

6. Conclusions

This work has shown how to use tremor measurements in order to check the presence of some vulnerability parameters that characterise bridge seismic responses. The method has been applied on two bridges in order to evaluate its limits and applicability (also on a large scale). The results lead to the conclusion that it is possible to directly identify some parameters (i.e., objective characterization), giving a synthetic description of the dynamical behaviour of the site and of the structure. Tremor measurements on site permit to use the HVSR method for the identification of the fundamental frequencies and an estimate of the impedance ratio, while data recorded on bridge can be analysed with SSR method. Furthermore, the joint analysis of site and structure is the preferable way to identify the potential presence of double-resonance effects.

The method is rapid and cheap: the data acquisition usually needs approximately couple of hours of work-field and about one hour of office-work in order to derive some dynamical characteristics of the structure. Anyway, the instrumental approach has not to be considered as an alternative to numerical analyses; rather the information obtained in a fast and cheap way with tremor measurements, can be fruitfully used in order to improve numerical simulations in a more detailed second stage, but only when it results necessary and useful. For example, significant differences between measured and numerical eigen-modes and eigen-frequencies can suggest an error on the numeric model or different elastic-mechanical properties of the material. In fact, the analyses of tremor measurements have the advantage to provide direct real information on site and structure, that does not suffer from assumptions that are necessarily used in numerical simulations or in empiric relationships.

Particular attention should be given to proper design of the measurement surveys and the positioning of instruments, in order to avoid misinterpretation of measurements. The method has been verified for a “specific” typology of structure, i.e., bridge on piles with constant height and similar spans; the application on other typologies is possible, with attention on the positioning of measurement points (for example in the case of piles with different height).

It is also important to note that all the considerations are valid within the linear elastic behaviour of structure and site; in case of an earthquake, it is very possible that the structure behaves non-linearly, and the values of eigen-frequencies change [accordingly to Mucciarelli *et al.* (2004)]. Nevertheless, this problem regards equally active and passive methods and all the numerical simulation that use the assumption of linear elastic material.

It is important to underline that the present method should not to be considered as a "stand-alone" method for identifying seismic vulnerability, but a support to other methods, especially for the fact that it permits to evaluate the joint behaviour of structure and site, i.e., the scenario. The cheapness and quickness permit the application on a large amount of structures, providing therefore the possibility of a vulnerability check at a regional scale.

Finally, the positive results presented in this paper suggest the possibility of the application of the PICS-Vul method on a large number of bridges in order to create a database of "seismic-fingerprints" that can also be used for damage assessments, comparing the pre and post-event measurements.

Acknowledgements. The authors would like to thank the Province of Udine for the collaboration in the Salt bridge measurements and E. Del Pin for the technical support.

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Corresponding author: Stefano Grimaz
Laboratorio di Sismologia Applicata, Dipartimento di Chimica, Fisica e Ambiente, Università degli Studi
Via Cotonificio 114, Udine, Italy
Phone: +39 0432 558731; fax: +39 0432 558734; e-mail: stefano.grimaz@uniud.it.