Standardized Serviceability Tests of Railway Bridges

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ABSTRACT: The research project "*ComTest*" has been performed as a joint initiative of the Austrian railway authority and several engineering consultant companies and research institutes. It was also linked to other national and international initiatives, especially ERRI (European Rail Research Institute). Its aim was to standardise dynamic tests on railway bridges and to develop an innovative technology for carrying out efficient, accurate and sustainable commissioning tests. In order to answer the related questions, "*ComTest*" was in a first step focused on examining a number of bridges in order to elaborate a significant database, which can be used by all interested parties. In a 2nd step, the gained experiences were gathered and evaluated, resulting in "*National Guidelines*" for performing such dynamic tests. The question, whether and how dynamic tests can substitute traditional commissioning serviceability tests was dealt with in a 3rd step.

1 INTRODUCTION

Subjecting newly built railway bridges before opening to static load tests has been common practice of the Austrian railway authorities up to now. For performing these tests, a number of locomotives or fully loaded goods wagons are positioned on the structure, and the resulting deformations are measured. These results are compared with the mathematical model results, and differences evaluated. If these differences remain within defined thresholds values, the structure corresponds to the planned conditions – thus the structure may be opened for regular traffic.

Limiting the requirements for serviceability tests to these static measurements has several shortcomings, e.g.:

- The measured data do not correspond to the real load, since the tests are not carried out under the real operating conditions.
- Performing these tests requires a disruption of the railway line, i.e. doing them systematically after certain periods during life time is laborious and costly.
- Dynamic effects are not at all considered. However, due to the steadily increasing velocities and axle loads, dynamic effects (resonance effects, fatigue, stress peaks, safety and comfort) become more and more important as design parameters.

For these reasons, but also with regard to TSI (Technical Standards for Interoperability), it was deemed to be essential to develop an innovative technology for carrying out efficient, accurate and sustainable commissioning tests, which will be useful and reasonable for infrastructure operators. An essential part of the project is to enable the investigation of bridges later under operational conditions (i.e. during operation). The research project aimed at giving an answer for problems, which have not been solved in previous programmes (e.g. determining damping coefficients, influence of ballast, construction material, application of dynamic measurement to short spans, etc).

In order to answer these questions, “*ComTest*” was focused on examining a number of bridges for elaborating a significant database, which can be used by all interested parties. In a first step, the different partners of the research project investigated a couple of bridges in parallel and independently. The different approaches were compared, the experiences exchanged and the advantages and disadvantages evaluated. The result was a considerable increase of experience in the application of dynamic testing. This experience forms the base of the *National Guidelines for Carrying out Dynamic Measurements on Railway Bridges and for Data Interpretation*, which have been developed within the research project.

In a 2nd step, the different partners performed tests on different bridges, in order to get a wide-spread database, containing significant results for a large range of bridges of different types and span lengths. Some of the insights gained in the testing process and by comparing the measurement results for different types of bridges are presented in section 2.2.

Investigating the possibilities of using standardised dynamic tests for replacing traditional static commissioning tests was the third main target of the research project. The related details are given in 2.3.

2 BRIDGE MEASUREMENTS

2.1 *Round-robin test*

First, a round-robin test was started to find a consistent standard for dynamic bridge measurements. All five partners of the project team participated and conducted measurements at the same bridge. The results of this test show that a comparison of the different measurement techniques was essential for identifying weak spots and harmonizing examination and analysis of data. The eigenfrequencies of the bridge under train passage and with ambient excitation were both determined. The values of the different partners are shown in figure 1 and they correlate quite well, especially when considering, that the measurements were done on different days and with variable trains. Consequently, the values for the first eigenfrequency without train mass have a smaller variance.

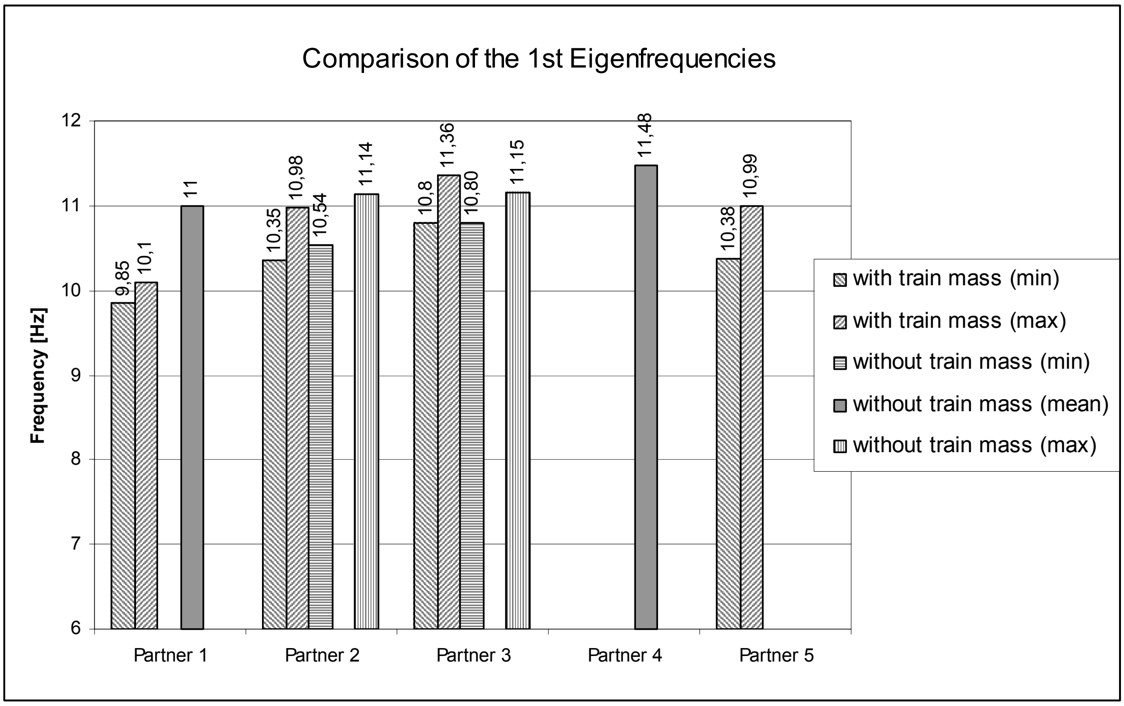

Figure 1. First eigenfrequencies of a structure measured by different partners

The comparison of the damping coefficient was much more complicated, because different analysing procedures have been used. To define a standard for the determination of the damping coefficients was one of the main targets of the further project works.

2.2 *Results of bridge measurements*

The vertical accelerations of characteristic points of the superstructure are relatively easy to be measured and have therefore often been the only parameter determined in dynamic tests. However, due to lacking information on the actual impact parameters (e.g. weight and axle distance of passing trains) the significance of this parameter is not very high. Therefore, the basic parameters to be used for assessing the bearing capacity the structure are generally the lowest natural modes. Measurements generally focus on determining these values. Details on how to perform meaningful frequency measurements are given in chapter 3.

The damping behavior of the structure is a further very important parameter for allowing for performing reasonable dynamic design calculations. The damping behavior is usually described by the damping coefficient ζ, characterizing the actual damping as a percentage of the critical damping. The damping coefficient can be recalculated from vibration measurement, using the decay of the oscillation amplitudes after the excitation has stopped. Details are given in 3.2.

A proper interpretation of the measurement results requires in general detecting and considering all possible sources of measurement errors, as well as thoroughly evaluating the governing impact parameters and boundary conditions. Special attention has to drawn on the following points:

- Temperature (frozen roadbed, temperature stress in statically indeterminate structures)
- Statistical spread of individual events
- Environmental conditions (snow, rain, …)
- Support conditions

For the assessment of accelerations it is important to take into consideration, that any measurement results represent an accidental snapshot of a certain train passage. At least the type of train with characteristic axle loads and distances, and the travel speed of the train must be known. The actual travel speed must in any case be measured. Appropriate methods are measurements with light barriers, cross correlation of different signals or measurements with radar pistols. Some characteristic measurement results are presented below.

The first example is a skew single-track, single span reinforced concrete slab as shown in figure 2. The identification of the lowest natural frequency gave values between 10.5 and 11.5 Hz. The determined structural damping values were 4 to 8 % of the critical damping.

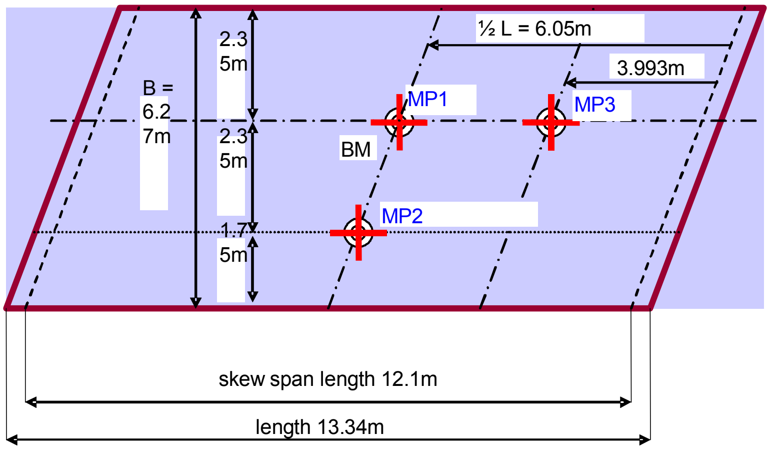

Figure 2 Plan view of the investigated concrete slab with measurement points

The following particularities were encountered:

- Due to the high damping, the duration of post-carriage vibrations was very short. A reasonable frequency and damping analysis was therefore limited to few individual events.
- Along the support lines, the slab was connected with rigid crossbeams to an adjacent identical slab. The respective coupling influenced the vibration behavior. The coupled eigenfrequencies could be detected in the spectrum.

The second example is a double track frame structure with a span length of about 15.00 m. The width of the trough cross-section is 13.90 m. Four acceleration sensors were placed at strategic points on the bottom side of the slab. Extensive evaluations of the measurement results have been performed, however, the identification of many different natural frequencies close together did not allow for nominating a characteristic value of the fundamental mode.

The particularities of this investigation were:

- A very complex vibration behavior is encountered for this type of structure. Arranging only 4 acceleration sensors is inadequate for identifying the eigenfrequencies and the related natural modes.
- A multiplicity of local modes exists. Capturing them requires a big amount of sensors. The proposed standard procedure for dynamic tests – aiming at dynamic assessment with small expense - is not appropriate for this type of bridge structures.

The third example is a single-track single span WIB structure (rolled girders in concrete). The span length is 17.45 m. The cross-section is shown in figure 3. An identical (mirrored) structure is seated sideways on the same abutments. The fundamental frequency after train passage was detected with 7.7 to 7.9 Hz. Slightly higher values were determined from measurements after train passage on the neighbor structure (8.0 Hz to 8.2 Hz). The same values were calculated from measurements with ambient or impulse excitation (hammer stroke).

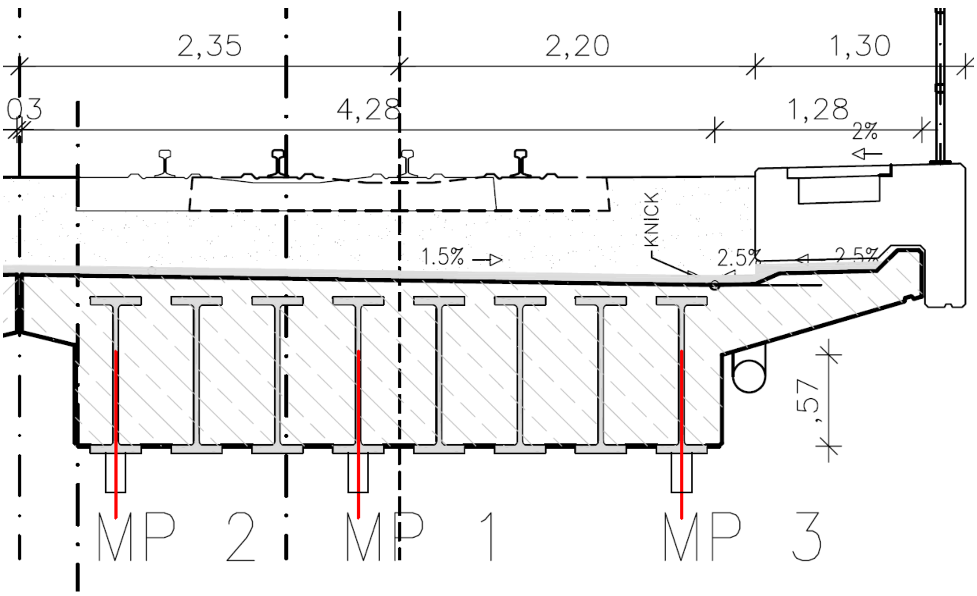

Figure 3 Cross-section of the investigated WIB structure with measurement points

The calculated damping values were 2.5 to 3.5 % of the critical damping. Due to the rolled steel girders, these values are quite below the values of those of pure concrete structures. Train passages on the neighbor structure induce vibrations on the measured structure. These may perfectly be used for evaluating the eigenfrequencies without train mass.

The 4th example is a two-span reinforced concrete bridge with 12.74 m span lengths. Seven sensors were applied. The fundamental frequency after train passage was approximately 9.9 Hz. The train passage on a neighbor structure and ambient excitation measurements gave 10.1 to 10.2 Hz. The difference between eigenfrequencies with and without train mass influence is in the same range than in the WIB girder example and in any case very small (3 to 4 %).

2.3 *Commissioning Test*

In Austria it is appointed, that dynamic measurement tests have to be accomplished for any bridges with a span larger than 12 meters. They can be omitted when a static deflection measurement is performed. However, a dynamic measurement is needed for all bridges where the

EN 1991-2 (2004) demands a dynamic analysis independent from its span. The following data has to be determined and analyzed:

- n_0 first eigenfrequency of the structure under dead load
- ς damping coefficient of the structure from the freely vibrating signal
- γ_{bt} resp. γ_{df} maximum vertical acceleration of the bridge deck
- n_{Zk} first eigenfrequency of the structure under train passage of train k

The *National Guidelines* to be developed in the research project (chapter 3) shall be used for the determination of these values.

The vertical acceleration must not exceed the values according to the EN 1990 A2.4.4.2.1, where the maximum allowed accelerations are 5,0 m/s² for slab track and 3,5 m/s² for roadbed. The aim of the dynamic measurement is to get a general confirmation of the dynamic behaviour of the structure. Moreover, the dynamic response of some certain train types is recorded and specific parameters for the dynamic calculations are gathered. In addition to this, the results can be used for subsequent periodic dynamic measurements. If the measured values are compared with dynamic calculation of bridges, three points have to be kept in mind:

- The measured values are accidental snapshots of certain trains
- Bad material of wagons causes higher accelerations
- The calculated values do not account for any irregularities and mistakes

Right now these commissioning tests are used as an additional assessment of bridges for going into service. It is planned for the future that these commissioning tests will replace the static load tests performed currently for every new bridge in Austria.

3 NATIONAL GUIDELINES

The need for national guidelines was confirmed during the round-robin test made at the beginning of the project. As there did not exist any national standard so far, this guidelines shall set the standard for all dynamic measurements on bridges including the commissioning tests described in chapter 2.3. The specifications given in this guideline apply for all bridges regardless of the construction type or span of a structure.

3.1 *Measurement techniques*

In principle, measuring instruments for the direct determination of the indicators velocity v(t) or acceleration a(t) can be applied. Acceleration sensors shall be used for the determination of the maximum acceleration, because an additional source of error is introduced by the differentiation required when velocity sensors are used. If the deflections of bridges are required, these shall be measured predominantly with displacement sensors; an indirect determination through integration of the acceleration signal is not allowed.

The measured signal has to be saved before further analyses are made and filters are used. The data acquisition system must dispose of a working frequency range, which covers the doubled values of the maximum frequency to be considered, however, at least 200 Hertz. The sampling rate plays a major role for data acquisition. All systems should have an anti-aliasing filter; however, many sensors do not have one. Only frequencies smaller than the Nyquist frequency (half of the sampling frequency) are allowed in the sampling signal in order to guarantee that the origin signal can be returned correctly. If this sampling theorem is hurt, frequencies, which are higher than half of the sampling frequency, are erroneously interpreted as lower frequencies. Consequently, a digital low pass filter should be used in order to avoid signal distortion. Therefore the sampling rate is directed after the existing low pass filter or after the high border frequency opposed in the amplifier. The experience shows that the sampling rate must amount at least to the quadruple value of the maximum frequency to be considered, but at least to 500 Hertz.

Three different methods can be used for the excitation of the bridges. The passage of a train on the structure is the most common used excitation, but it must be kept in mind, that the mass of the train is affecting the natural frequencies. For the measurement of ambient vibrations through wind, very sensitive sensors for micro-seismic or other causations are needed. The third method is to use the excitation of artificial impulses created by people jumping on the bridge, by strokes with a hammer or by a reaction mass exciter. The last mentioned method is only used in special cases. From experiences in the project, it can be stated that jumping and strokes with a hammer provide very good results, when enough time is left between the excitations (approximately 20 seconds). Measurements of ambient vibrations result in very accurate values for natural frequencies, when a time period of at least 20 minutes is used.

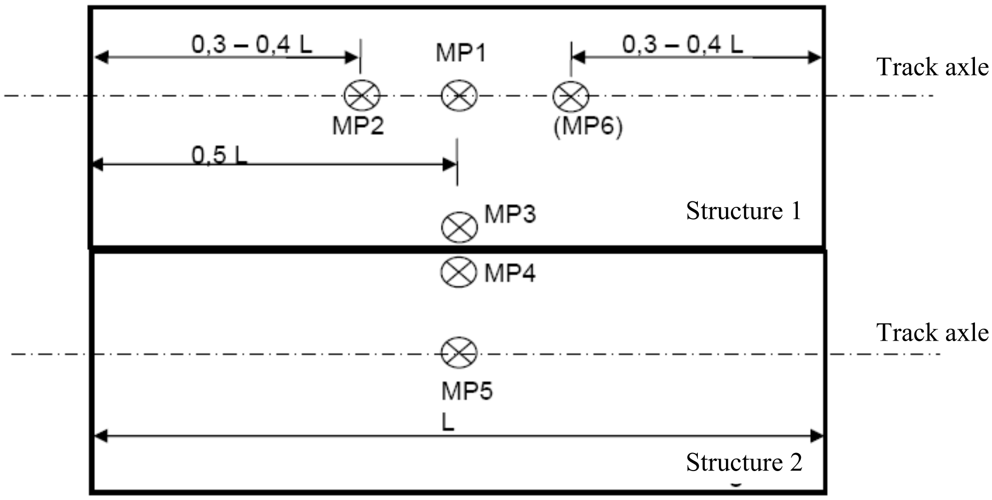

Figure 4. Measurement layout for a single span bridge

The positioning of the sensors is very important for obtaining the right signals for the analysis. For a single span bridge, the positioning can be specified as shown in figure 4, whereas for more complicated structures just general rules can be given.

Applying these general recommendations, the engineer has to decide from case to case, how many sensors are required, and where they shall be located. Two of these general rules are stated below:

- Fundamentally, the sensors should be positioned at the places, where the expected relevant natural modes yield maximum values of the measured quantities. For structures with more spans or irregular structures, the position of the maximum displacements and accelerations can deviate from the center of the span.
- Instruments shall be fixed directly on the structure; only in exceptional cases a fixing on secondary construction units (e.g. edge beams) is permissible.

A measurement protocol, including all important facts and parameters, must be drawn up for every measuring.

3.2 *Data analysis*

Basically, it can be distinguished between data interpretation in the time domain or in the frequency domain. Some parameters can be adequately determined in both domains. the data analysis is subjected to very sharp regulations in order to obtain comparable results for dynamic bridge measurements.

The determination of the maximum acceleration during train passage has to be made with a low pass Butterworth filter with 8^{th} order. Identification of damping coefficients is only allowed from the free vibrations, i.e. when the train has already left the bridge as explained in detail in the UIC Guideline for dynamic bridge measurement (Guidelines for Railway Bridge Dynamic Measurements and Calculations, 2007). Sometimes it can be very difficult or even impossible to identify appropriate damping coefficients. Figure 5 and equation (1) show the determination of the damping coefficient ς.

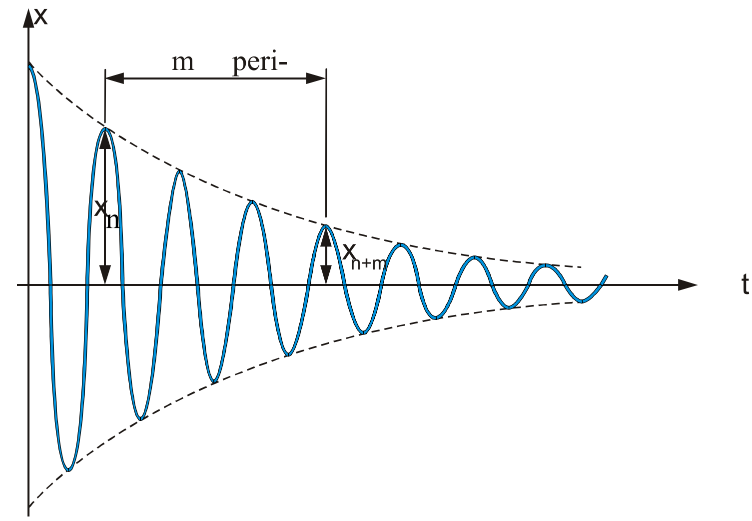

Figure 5. Determination of the damping coefficient

$$\zeta = \frac{1}{2\pi \cdot m} \cdot \ln\left(\frac{x_n}{x_{n+m}}\right) \qquad (1)$$

As there occur different damping values for different train passages, it was agreed to always taking the lowest value. At least five analyzable free vibrating signals, which have at any rate three complete periods, are necessary for getting representative results

The eigenfrequencies are identified in the frequency domain, and in special cases the determination of the damping coefficient can be made with the method of full width at half maximum (root-2-method). The natural frequencies should be assigned from the ambient measurements or the impulse excitations. A determination from the free vibration after a train passage is not allowed, because the changeover from the forced vibration (train passage) to the free vibration is affected with uncertainties. Generally it leads to lower natural frequencies.

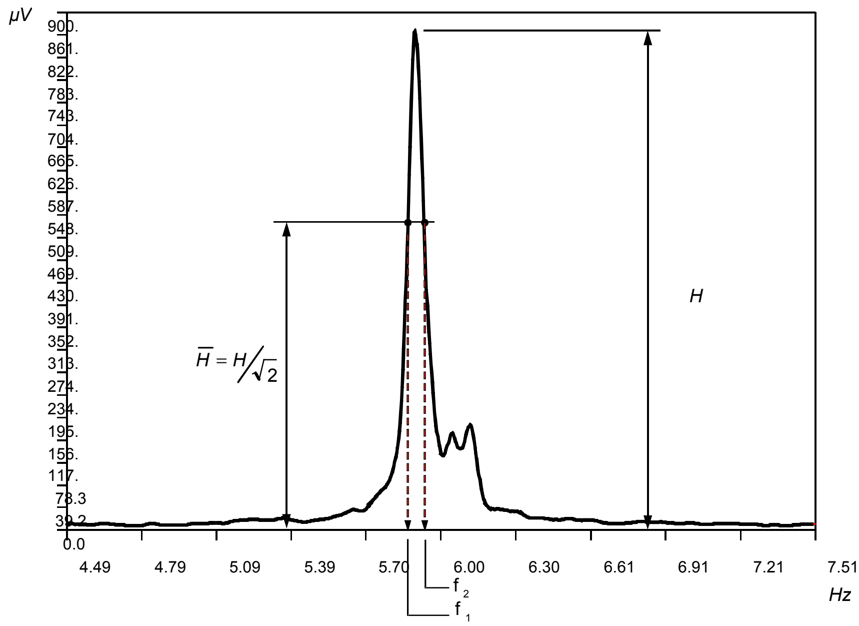

Figure 6: Description of the method of full width at half maximum

The application of the root-2-method is easier but is afflicted with fuzziness. Some important points have to be taken into account to get reasonable results. Smoothing or averaging must not be used as well as any windowing and amplification is not admitted. Furthermore this method cannot be applied when natural frequencies are close to each other or for frequency spectra determined only from ambient vibrations. If filters are used before the transformation into the frequency domain, it will be essential to avoid changes in the amplitude through inclination of filters. Figure 6 and equation (2) show the identification method.

$$\zeta = \frac{f_2 - f_1}{f_2 + f_1} \tag{2}$$

When analyzing the measured data it is essential to make some plausibility checks and to consider the basic conditions during measurements. The temperature can have a huge impact on the results, especially below zero and for statically indeterminate structures.

4 SUMMARY

The results of dynamic measurements can perfectly be used for the comparison with the demands of standards and regulations for bridge assessment (commissioning tests for newly built bridges or regular bearing capacity tests in the life cycle). Moreover dynamic measurements give the required input data for dynamic calculations modeling the actual behavior of the structure. The results of these calculations can be compared with those of design calculations representing the nominal behavior. Periodic measurements of bridges are used for assessment of life cycle costs, support health monitoring and give estimations for similar bridges.

5 REFERENCES

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