Inspecting the Foundations of Motorway Bridges to Investigate Karst Structures by the Use of Seismic Methods

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Abstract
In Germany alone, approx. 2,500 bridges require maintaining or replacing. Additionally, federal highway management plans consider the construction of many further new bridges within the next decade. At planning stage an intense assessment of the ground geology and its present-day condition is needed for the safe geotechnical integration of the bridge foundations in the ground. The knowledge about the underlying geological formations is partially very poor, especially for older bridge constructions. By the use of geophysical investigation methods valuable information of the ground can be derived from in-situ measurements to minimize risks and, thus, the construction costs. One very effective investigation method for the detection of cavities and zones with low structural integrity is the seismic tomography method which utilizes elastic waves through the ground (= seismic waves) for the derivation of ground material properties like density or shear strength. As one major advantage such investigative methods are non-destructive and can significantly reduce the efforts for the ground assessment with intrusive methods like with boreholes.

Keywords: bridges, foundation, geology, karst, voiding, hazard, seismic crosshole, geophysics, elastic moduli

1 Introduction
In Germany, the federal highways authority is responsible for up to 40,000 bridges. Many of them have been built more than 40 years ago and will likely require some form of maintenance in the near future [1]. This is mainly for two reasons. Firstly, the material of the construction elements, e.g. concrete and reinforcement, of the bridge structure has reached its lifetime end due to deterioration and weathering effects. And secondly, the actual traffic load has increased significantly in the latest decades [2] exceeding the limits of particularly the older bridges which have been designed under consideration of the traffic load at former times.

One program has already been started recently to renovate or even replace about 15% of the bridges which are in insufficient and unsafe condition. It is likely that the demand for bridge maintenance will increase in the next decade and that the reconstruction program will require extending and expanding also to road classes other than the highways [3].

Within the maintenance program an extensive investigation sequence will be required for each single bridge [4]. The actual structural condition of the bridge building and also the ground condition need to be assessed in order to allow adequate planning of the required measures for that bridge. While for one bridge basic repair of local cracks may be sufficient to significantly extend the bridge lifetime, another bridge may need to be replaced by an entire new bridge structure.

The knowledge about the underlying geological formations below the bridge foundations in many cases is very poor, especially for rather old bridge buildings. Constant deterioration and weathering from daily changes in temperature and weather condition may have altered the ground condition, too. Intense water flows may have developed local voiding or cavities below the bridge foundations which may become a risk for the stability of the bridge structure [5].

With the aid of applying geophysical and non-destructive investigation methods valuable detailed information of the true ground structure and condition can be generated to support further geotechnical planning and bridge design processes. The following descriptions will outline the possibilities, advantages and benefits of deploying geophysical testing facilities.
for the assessment of the ground geology below bridge foundations. In particular, seismic methods have been found advantageous in recent investigation programs. The results of the case studies will be presented as examples.

2 Seismic Tomography
Generally, seismic tomography is a specific seismic investigation method which analyses the recorded travel times of seismic waves travelling through the ground. Two distinct types of techniques can be identified within the seismic tomography methodology: the refraction tomography and the crosshole tomography.

The refraction tomography is based on an analysis of the travel times of refracted waves. These waves are generated at the earth's surface and run through the underground with material specific velocities. The schematic image in Figure 1 illustrates the principal concept. At boundary interfaces which can be characterised by a significant increase of the velocities of propagation, the waves are diffracted and one portion of the seismic energy is radiated back to the surface. These refracted waves returning to the surface are recorded with geophone sensors [6].

Instead, the crosshole tomography is deployed from boreholes and investigates the ground between the boreholes [7]. Inside one borehole a seismic source generating seismic wave energy is positioned at various elevation levels. In a second borehole equidistant receiver sensors (e.g. hydrophones or geophones) are deployed.

The tomography results of both methods are calculated with an inversion approach [8]. The process calculates from the set of observations the causal factors that produced the observations. It is called an inverse problem because it starts with the results and then calculates the causes. This is the inverse of a forward problem, which starts with the causes and then calculates the results. Usual methods for the numerical calculation are SIRT (simultaneous iteration reconstruction technique), MSIRT (multiplicative simultaneous iteration reconstruction technique) or back projection algorithms [9].

The result of the inversion computation is typically displayed in a sectional image. The image shows the distribution of seismic velocity values on a section between the boreholes. The velocity values are coded with different colours representing high and low values. Since the height of the seismic velocity is directly linked to material properties like density, shear
strength and compressibility [10], the coloured image result of the tomography analysis indicates potential areas with differing stability. For example, zones in the ground with low seismic velocity values in respect to the surrounding ground material can typically be associated with low integrity of the ground or even cavities [11].

3 Inspection of bridge foundations
The assessment of bridge foundations with seismic tomography method has been carried out at two representative sites in the south-east region of Germany.

3.1 Case study 1
The first example of using seismic tomography is from a case study on the federal highway A3 at a bridge section with east west orientation between Nuremberg and Regensburg (see Figure 2). After basic ground investigations with core samples taken at various locations along the axis of the bridge showed unconsolidated ground structure in some places concern was raised about potential existence of voiding or larger cavities below the abutment and pillars of the existing bridge. In consequence, an investigation program has been established that included in the first phase seismic refraction tomography along a series of longitudinal profiles parallel to the axis of the bridge followed by additional drilling and crosshole tomography measures in the second project phase. In this context, the results from the longitudinal profiles were used to target the additional boreholes for the detailed crosshole tomography work (see right hand side of Figure 2).

The goal of the geophysical investigation project was to find and assess potential areas of soft material within the sound rock of the hardstanding. It was planned to use the results for better targeting geotechnical measures such as grouting to improve the ground integrity.

![Figure 2: ground investigation site under the existing bridge deck (left) where several crosshole tomography measurements have been taken in a series of adjacent boreholes next to the abutment and the pillars of the bridge (right).](image-url)
The refraction tomography measurements had been carried out on the surface along three between 210 m and 254 m long longitudinal profiles running in east-west orientation and parallel to the bridge axis. The geophones have been laid out at 2 m centres while the source points had 5 m distance from each other. An accelerated weight mass impactor had been used as the source for the generation of the seismic wave energy.

The result of one of the lines has been presented in Figure 3. The image shows the distribution of seismic wave travel velocity at depth. Each velocity value which has been given in meters per second, has been assigned to a specific colour in order to quickly distinguish visually the differing areas within ground. The image results also includes vertical colour bars integrated into the tomography image which represent the results from investigative coring. The geophysical data results have been calibrated using the core results allowing to fine-tune the colour code and depth velocity relation. Differences between the core result and the tomography image may still occur if the location of the borehole does not exactly intersect the survey line of the profile.

The results from the seismic refraction tomography survey revealed some areas where low values of the seismic wave propagation velocity can be found at greater depth from the surface, particularly to the east of the survey site. Also in these areas, the discontinuity boundary between the high velocity values and low velocity values seems to be significantly less linear compared to the adjacent sections where the boundary appears to be linear and sharp. An interpretative view of these findings would suggest that the underlying rock formation may be more fractured and disintegrated towards the east abutment of the bridge.

![Figure 3: image result from the refraction tomography measurements along a longitudinal profile. One larger area to the end of the profile showed low seismic wave travel velocity at greater depth indicating potential voiding within the sound rock.]

More detailed information about the condition of the rock beneath the east abutment of the bridge gave the results from the crosshole tomography investigations, which have been carried out in the second phase several weeks after the findings from the refraction tomography survey. In total, nine tomographic sections have been investigated between a set of nine boreholes (see right hand side of Figure 2). The depth of the boreholes was in a range of 36 m to 50 m drilled into the hardstanding rock. Each borehole had a casing of PVC material with an inner diameter of 120 mm installed and the outer diameter had been grouted with a bentonite mixture. Interesting to mention was that one would think the instalments to...
be impermeable for water. But in fact large portions of water had to be constantly filled into some of the PVC tubes suggesting water drainage primarily at the bottom of the tube vanishing through cracks in the grouting. This already indicates that the ground and rock condition appeared to be rather fractured and unconsolidated in this area. For the borehole tests a hydrophone cable with multiple sensors at 0.5 m centres had been deployed into one borehole and a seismic borehole source had been lowered down into another adjacent borehole. With this kind of set-up a distance of less than 15 m between the two boreholes is typically required to ensure the recorded seismic signals being of sufficient quality for producing reasonably reliable information results.

A 3D view of all the tomography image results from this crosshole survey can be found in Figure 4 looking from the North side of the bridge in southbound direction. In the 3D image, direction East is to the left, accordingly. Similar to the refraction tomography results from the longitudinal measurements, the image results from the crosshole tomography generally show the distribution of seismic wave velocity values in the section between the boreholes. Extra care has to be taken when trying to extrapolate these values into locations perpendicular to that section. The image result in Figure 4 shows low seismic velocities (yellow/green) at greater depth particularly to the north-east (left hand side in the image) of the bridge abutment. Together with the results from the drilling operations of the boreholes it was anticipated that the shallow hardstanding rock would likely be washed out and partially fractured.

![Figure 4: 3D view of the results from seismic crosshole tomography survey](image)

In summary of the case study 1, the seismic investigations have been carried out in a logical sequence, starting with an overview survey on the entire length of the bridge, and from there targeting more detailed measurements in selected locations. The results revealed partially deteriorated ground below the existing bridge suggesting further requirements to support the ground with geotechnical measures.
3.2 Case study 2
The second case study represents a crosshole tomography investigation on a highway bridge under construction at highway No A3 between Frankfurt and Wurzburg in Germany. During the construction works several clefts had been found under the foundation piles. To apply the seismic tomography method ten boreholes were drilled into depths between 12 and 20 m. The boreholes were arranged along two lines with five holes along each profile. 13 crosshole tomography sections were measured between the pairs of borehole (Figure 5).

Figure 5: Location map of the survey area with foundation piles (gray), tomography drill holes (blue) and location of the tomography sections (T_01 to T_13).

For data acquisition again similar set-up as in the above case study 1 had been used. In Figure 6 the results of the tomography sections T_01 to T_04 and T_06 to T_09 are presented. The two images (a) and (b) show the seismic wave propagation velocity values at each point between the boreholes. Section (a) represents the results from the red bottom line of Figure 5 which is located further north whereas section (b) represents to green top line. The distance between the two sections was five meters.

Indications for potential clefts can be seen on both sections. These clefts are situated below an elevation of 335 m and are shown as green areas dipping into the grey coloured matrix. The inclination of these structures was found to be approximately 65 degrees in southwest direction. With the seismic results the cleft zones have been identified and located.

Figure 6: Results of the crosshole tomography showing indications for clefts under the concrete piles
In a second step a restoration of the area under the piles was planned. The potential cleft zones had been verified with drill holes and subsequently filled with a concrete suspension. After the restoration a second seismic measurement was carried out to control the success of the concrete restoration process. In Figure 7 the result of the verification survey is illustrated. The clefts around the bottom areas of the piles (which are visible in section (a)) are filled with grouting material of higher seismic velocity (section (b)), so that the previously green areas have disappeared. Image (b) demonstrates that the piles are in good contact with the base rock.

Figure 7: Results of a seismic crosshole tomography investigation before (a) and after (b) restoration of the unconsolidated area below the bridge piles with geotechnical measures.

3.3 Case study 3
Another data example shows the result of refraction tomography survey (pressure wave and shear wave) also at a bridge location along highway No A3 in Germany. The survey was completed in the planning phase of the construction project and the aim was to get continuous information about the stability of the underground described by the static Young's modulus.

Figure 8: Distribution of the static Youngs modulus derived from seismic refraction tomography and well core strain tests
From the results of the refraction tomography, which gave information about the distribution of the shear and pressure velocities, and additional borehole information about the density, the distribution of the dynamic Young’s modulus was estimated. Because the static and dynamic modulus of the same rock differs significantly from each other [12], a relating function between them was calculated with the information of several strain tests which were carried out at the well cores. The empiric relation allowed a conversion from the dynamic modulus to the static modulus. The conversion is valid only locally for this particular site. Figure 8 shows the resulting distribution of the static Young’s modulus.

4 Conclusion and Outlook
Geophysical investigation methods have the ability to provide detailed structural and condition information about the ground formations. In a geotechnical context important elastic moduli can be derived from the seismic measurements allowing an effective and reliable assessment of the principle suitability of the ground for construction purposes. Applications include preventive investigations on unused green field prior any construction activity, detailed assessment of the up-to-date condition of existing construction sites as well as quality control to verify bridge maintenance measures.

Additionally, such geophysical investigation methods minimize the risk for early damages or even failure of the bridge and reduces the overall maintenance costs since the provided information allows better planning of the maintenance operations. A rather comprehensive approach even suggests to include the various phases of the ground investigation process within a sophisticated bridge management system that monitors and controls all required maintenance processes during the entire life time of a bridge.

5 Acknowledgements
We like to thank "Autobahndirektion Nordbayern" for cooperation and provision of the survey results.

6 References
(2) Rickert, L., Abschätzung der langfristigen Entwicklung des Güterverkehrs in Deutschland bis 2050, on behalf of BMVBS, 2007
(5) G.S. Xeidakis, A.Torok, S.Skias and B. Kleb, Engineering geological problems associated with karst terrains: their investigation, monitoring, and mitigation and design of engineering structures on karst terrains, Proceedings of the 10th International Congress, Thessaloniki, April 2004
International Symposium
Non-Destructive Testing in Civil Engineering (NDT-CE)
September 15 - 17, 2015, Berlin, Germany


