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Assessment of an ancient bridge combining geophysical and advanced photogrammetric methods: Application to the Pont De Coq, France

Cyrille Fauchard [a,*], Raphaël Antoine [a], Frédéric Bretar [a], Julien Lacogne [b], Yannick Fargier [c], Cindy Maisonnave [a], Vincent Guilbert [a], Pierre Marjerie [d], Paul-Franck Thérain [e], Jean-Paul Dupont [f], Marc Pierrot-Deseilligny [g]

[a] Centre d'Études Techniques de l'Équipement - Normandie Centre, ERA23, Université de Rouen, 10 chemin de la Poudrière, CS 90245, 76121 Le Grand Quevilly, France
[b] Centre d'Études Techniques de l'Équipement - Normandie Centre, DADT, Université de Rouen, 10 chemin de la Poudrière, CS 90245, 76121 Le Grand Quevilly, France
[c] Centre d'Études Techniques de l'Équipement - Normandie Centre, ERA44, 11 rue Laplace, CS 2912, 41029 Blois France
[d] Laboratoire ECODIV, Institut de Recherche et d'Enseignement en Sciences de l'Environnement, Université de Rouen, Place Emile Blondel, F-76821 Mont Saint Aignan Cedex, France
[e] Direction Régionale des Affaires Culturelles - Haute Normandie, Conservation Régionale des Monuments Historiques, 7 Place de la Madeleine, 76000 Rouen, France
[f] Laboratoire de Morphodynamique Continentale et Côtiére, UMR 6143-CNRS, Université de Rouen, Place Emile Blondel, F-76821 Mont Saint Aignan Cedex, France
[g] École Nationale des Sciences Géographiques, 6 et 8 Avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne, 77455 Marne la Vallée, Cedex 2, France

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ABSTRACT

A high resolution geophysical survey was carried out on the Pont De Coq, a medieval stone arch bridge located in Normandy (France) in 2011 and 2012. Two complementary methods are used: Electrical Resistivity Tomography (ERT) and Ground PenetratingRadar (GPR). They allow to evaluate the structural state of the bridge and to characterize the subsurface around and beneath the bridge. An excellent correlation is obtained between the geophysical methods and the geological data obtained around the bridge. In order to improve the restitution of the geophysical data, an advanced photogrammetric method is performed, providing a high resolution 3D Digital Terrain Model (DTM) of the Pont de Coq. The advanced photogrammetry enhances the presentation of the GPR and ERT data. This approach is an easy-to-use, rapid and cost-effective tool for stakeholders. Finally, it is a promising and original method for improved interpretations of future geophysical surveys.

1. Introduction

In the last decades, public institutions have shown an increased interest in heritage conservation and monuments protection. For that purpose, geophysical methods have been used for 20 years as powerful tools to assist in the curation of buildings (Colla et al., 1997; McCann and Forde, 2001; Nuzzo et al., 2010; Orbán and Gutermann, 2009; Orbán et al., 2008; Ranalli et al., 2004).

Bridges exhibit complex structures (Boothby et al., 1998), built in various geological conditions. This characteristic makes the combination of geophysical methods necessary to obtain a meaningful model of the internal structure of such constructions and their environment. For instance, Flint et al. (1999) used the Electric Resistivity Tomography (ERT), the Seismic and the Ground Penetrating Radar (GPR) methods to observe masonry structures. GPR and infrared thermography were performed by Hing and Halabe (2010) to detect water infiltration and defects at the surface at the surface deck of a Glass-Fiber-Reinforced Polymer bridge. On masonry bridges, the GPR is one of the most used tool, due its high practicality in the field (Hugenschmidt and Mastrangelo, 2006; Solla et al., 2010, 2011a,b). Indeed, it can be applied on the different parts of the bridge (deck, wingwalls, sprandel walls, barrel) and provides a quick observation of potential disorders (voids, roots, water infiltration, etc.) within the bridge.

The first objective of this paper is to investigate the internal structure of a small masonry arch bridge called "Pont de Coq" crossing the Epte river located in Normandy, France. This 400 year-old bridge has been severely damaged by the vegetation during several tens of years and will be subject to a complete rehabilitation in the near future. Thus, the small dimensions of the structure (a few meters) make the use of the GPR clearly suitable for a preliminary characterization of the extent of the internal disorders.

The second objective of this work is the determination of the nature of the soil around the river and under the bridge. In particular, the characterization of the foundations lying beneath the abutments is critical, because it will strongly constrain the rehabilitation stages. In such an alluvial context, the ERT and GPR methods are suitable for a rapid imaging of the shallow subsurface (Doetsch et al., 2012; Ercoli et al., 2012; Gourry et al., 2003). We performed several GPR and ERT profiles along the road crossing the bridge, as well as in the transverse direction to the structure. GPR observations were also made along the arch barrel of the bridge. Finally, the subsurface of the two banks of the river near

* Corresponding author. Tel.: +33 235689295; fax: +33 235688188.
E-mail address: cyrille.fauchard@developpement-durable.gouv.fr (C. Fauchard).

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the bridge was observed using the ERT method. The geophysical measurements are compared with the sedimentary logs obtained from two boreholes drilled around the bridge.

The photogrammetric method is a technique allowing the three-dimensional (3D) reconstruction of an object from photos. Recently, techniques based on close-range stereophotogrammetry have proved their capacity to extract DTMs with submillimeter accuracies (Chandler et al., 2005). Such DTMs have the advantage of providing a large number of profiles over large areas in one measurement only. For instance, such tools have been successfully used with geophysical methods for the structural assessment of stone arch bridges (Arias et al., 2007; Lubowiecka et al., 2011; Solla et al., 2012). Despite impressive results, they require careful positioning and orientation of the cameras with respect to the surface, the use of bulky poles and vertical calibration to minimize perspective distortion due to the focal lens of the camera. There are several commercial and open source software package like Photosynth (Microsoft Live Labs/University of Washington) or Photomodeller Pro (Eos Systems Inc.) to generate 3D models of the photographed object. Moreover, they lack mathematical rigor in the formulation of the equations which leads to low accuracy for scientific application. Geophysicists and civil engineers increasingly need affordable, light but also accurate tools to study the subsurface or to survey buildings (Pierrot Deseilligny and Clery, 2011). As a summary, most of these techniques are difficult to use and none of them is fully satisfactory in terms of costs, applicability or spatial sampling. Recently, substantial progress has been made in the generation of DTMs, using photographic images taken by off-the-shelf digital cameras positioned at different locations around the target with a resolution ranging from millimeters to a few centimeters. For the first time, this article presents a rapid and cost-effective photogrammetric method described in Bretar et al. (2013) to improve the 3D presentation of geophysical data.

In Section 2, the historical context of the Pont de Coq and the geology of the region are presented. Section 3 is dedicated to the description of the geological data obtained at the local scale by the boreholes performed close to the bridge. Then, we present our geophysical data: the GPR measurements carried out on the bridge, in particular on the deck and the arch barrel are discussed in Section 4. This part is followed by the characterization of the surroundings of the structure by GPR and ERT (Section 5). Finally, a high resolution photogrammetric DTM of the Pont de Coq integrating the GPR and ERT data is presented in Section 6.

2. Study context

2.1. Historical context and location of the Pont de Coq

The Pont De Coq is an arch bridge located on an ancient royal road connecting Dieppe to Paris, between the Meneval and Saumont-La-Poterie towns (Fig. 1). It spans the Epte river, a 113 km long tributary of the Seine river. The bridge is thought to have been built at the beginning of the XVIIth century. The structure was preserved from wars, but it was progressively abandoned by the authorities during the last centuries, due to new roads and a railway constructions. Re-discovered in 2010, the Pont de Coq is now registered as an historical monument by the French Authorities and is restored by a non-profit organization (ASPC, Association pour la Sauvegarde du Pont de Coq).

In 2010, the first in-situ visits revealed several damages at the Pont De Coq. The wingwalls (upstream north wall and both downstream walls) are skewed and some stones have disappeared. The upstream south wingwall has been destroyed by a tree's root network (shown in Fig. 2). The roots also extend within the backfill material at the top of the abutment and under the roadway, which is paved with limestone stones perfectly jointed and overlaying a compacted silty layer. The road surface is regular with minor local deformations, probably due to the root network development into the silty layer and the backfill material. The voussoirs are joined with thin mortar and perfectly dressed and shaped. The intrados and extrados follow a semicircular arch ring. It can be noted that the voussoirs are shaped in polygonal extrados. This roman construction technique appears in the French civil engineering at the beginning of the Renaissance (XVIIth century). Despite the apparent bad condition of the bridge, only one crack is visible on the barrel surface at the downstream side. The arch is perfectly semicircular and the mechanical conditions of the bridge allow a low traffic of vehicles. An inspection at the bottom of the abutments also assumes the presence of driven wood piles anchoring the bridge in an unidentified layer.

2.2. Geological background

The Pont De Coq is built in the alluvial plain of the Epte River. The alluvions of the river at the regional scale are essentially composed of silty sand (Blondeau et al., 1979) that lays either on Quaternary colluvium or Upper Jurassic layers. The deposits are distributed as follows (Fig. 3):

- Quaternary limestone colluvium resulting from the erosion of Middle Portlandian deposits (clay, marl and limestone) or Middle to Upper Portlandian sediments (clay, sand and sandstone);
- An Upper Portlandian (Upper Jurassic) formation exhibiting sandy clay at the base of the layer and fine ferruginous sand at the top;
- A Middle Portlandian (Upper Jurassic) formation composed of i) a gray/blue clay layer at the bottom, ii) alternation of sand and sandstone layers at the middle and iii) marly limestone deposits at the top;
- A Lower Portlandian (Upper Jurassic) formation composed of an alternation of clear lithographic limestone and gray marl;
- A Kimmeridgian (Upper Jurassic) formation mainly composed of gray and/or blue clay.

3. Geological drilling

A complete study of the local geology and the geomorphology of the alluvial plain at the vicinities of the Pont de Coq has been achieved by Maisonnave (2012). In order to determine the nature of the subsurface at the local scale around the bridge, two boreholes were drilled near the Pont De Coq (numbered 1 and 2, in Fig. 5a) at the south and the north sides of the bridge (Fig. 5a and b). This geotechnical investigation was performed using a helical auger lent by the University of Rouen (Fig. 4). This method allows a good preservation of the lithological sequences. However, some sedimentary structures such as laminations or sorting may be partially destroyed when the soil is not cohesive enough. Thus, we only focus on the lithological nature of the observed sediments. The geological log of the first borehole (Fig. 5a) exhibits a silty layer road surface between 0 and about 40 cm depth, followed by a clayey layer between 40 cm and 1 m depth and a sandy layer with pebbles between 1 m and 2.5 m depth. Under this limit, the observed material is composed of Middle Portlandian clay. The geological log of the second borehole shows a similar layering, with a drilling refusal at 3 m depth.

The borehole logging provides a detailed description of the geology at the local scale around the bridge. However, such operation remains semi-destructive and punctual. In the next sections, we use the GPR and ERT geophysical methods to characterize the internal structure of the bridge (deck and arch barrel, Section 4) and the subsurface on which it was built (Section 5) without any destructive operation.

4. Non destructive assessment of the Pont De Coq masonry with GPR

For all geophysical surveys in this study, we define both the letters z and x respectively as the depth and the distance along the geophysical profile at which is observed an anomalie. In this section, we present the GPR survey carried out on the deck and the arch barrel of the Pont de Coq. Our objective is to determine whether voids, deformations or a tree's root network are present within the structure. Four longitunal