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Original article

Design and calibration of a drill-guided system by laser for structural strengthening of historic bridge

Jose Herráez[a,*], Jose Luis Denia[a], Pablo Navarro[b], Luis Bosch[b], Ignacio Bosch[b]

[a] Department of Cartographic Engineering, Geodesy and Photogrammetry, High School of Civil Engineering (UPV), 46022 Valencia, Spain
[b] Department of Architectural Projects, High School of Architecture (UPV), 46022 Valencia, Spain

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A B S T R A C T

Restoring the spans of a historic bridge requires installing tensors to ensure the structural and mechanical stability of the rows of stones that form the resistant body of the bridge. Once the positions where the structure-crossing tensors should be installed have been determined, the entry and exit points of each drill hole must be marked on both sides of the bridge. However, the exit point of each drill hole is not visible from the entry point, making it impossible to drill precisely. Here, we present a method based on a calibrated system that combines precision topography with laser technology. Using this method, drill holes longer than 12 m can be achieved with centimetric precision.

1. Research aims

Research aims consist on developing a methodology to install tensors in a historic bridge to ensure stability through drill holes that perforate the bridge from one side to the other with centimetric precision. Due to the great width of the bridge, the predetermined points of beginning and end of the drill holes are not visible from the opposite side. So it will be necessary to design and calibrate a drill-guided system.

2. Introduction

Topography and photogrammetry are commonly applied in civil engineering studies. Numerous papers concerning historic bridge conservation have been published over several decades. In general, topographic and photogrammetric methods play a role in any project undertaken on a bridge because they make it possible to establish coordinate systems that give spatial dimensions to the structure and other applications related to conservation and restoration activities (providing images as well as metric attributes) [1]. Until recently, most of these applications have focused on the study of dimensional analyses using photogrammetric techniques with topographic support. Topographic methods have been progressively abandoned because of the recent emergence of laser scanning combined with photogrammetry [2]. The laser scanner has proven useful not only for bridges, but also for other elements of civil engineering [3]. Laser scanning has found an increasing number of applications in structural studies [4], and recent studies have increasingly incorporated the ability to optimize the precision of the data obtained as necessary [5].

In addition to recent applications of laser scanning, many published studies have employed topographic and photogrammetric methods to obtain three-dimensional models of bridges [6]. Many structural studies have also centered on civil engineering and architectural heritage restoration perspectives [7–10].

Both approaches are complementary. Topography and photogrammetry enable a three-dimensional structure, such as a bridge, to be modelled; civil engineering can subsequently make use of such models. This complementarity is effective as long as the activities involved are independent of and external to the bridge or other structure. Topography and photogrammetry provide exterior dimensional information that other disciplines can utilize to design particular courses of action for the structure.

However, these two approaches are sometimes insufficient. Once a three-dimensional model has been obtained and used to perform the necessary calculations, particular operations must sometimes be performed in the inaccessible interior of the structure. In such cases, the three-dimensional model does not provide enough information to take action. In the present study, we develop a hybrid system that combines topographic networks with appropriate photogrammetric equations applied to a laser trajectory to install tensors in a historic bridge through drill holes that perforate the bridge from one side to the other. Because of the dimensions of the bridge, the predetermined ends of the drill cannot be

* Corresponding author.
E-mail addresses: jherraez@cgf.upv.es (J. Herráez), jdenia@cgf.upv.es (J.L. Denia), pnavarr@ega.upv.es (P. Navarro), ibosch@pra.upv.es (L. Bosch), luiboschro@pra.upv.es (I. Bosch).

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viewed simultaneously: we cannot directly control that the drilling direction is correct. Therefore, we designed and calibrated this drill-guided system to obtain exit points with centimetric precision relative to the predetermined installation points for the tensors in the bridge.

3. Drilling methodology for tensor installation

3.1. Calibration system

The bridge is 12 m wide: the exit point of each drill hole is not visible from the entry point (and vice versa). Thus, a simple system must be designed so that the drill operator can continually ensure that no substantial variations in the drill holes occur during the rotation and thrusting process.

The drilling system poses three fundamental problems: how to anchor the drilling system in the proper direction to guarantee its exit at the predetermined point; the possible gaps in the drilling system made up of 1-m-long coupled elements; and the gravitational fall of the drilling system as a whole. So, although the drill motor is bolted onto its supporting rail, its axis must be only tangent at the drill trajectory at its beginning (which will be surely a curve, but not the straight line joining the entry and exit points of the hole); thus, we cannot establish a hypothesis about the direction or levelling of the system based on the system itself. To do so, we must design a separate system to control the drilling system.

We first developed a topographic network to connect the entry point of the drill (T_1) to its exit point (T_2) by employing observations from different positions on both sides of the bridge to obtain the unitary drilling vector ($V^{\mathbf{U}}_{T1-T2}$). This vector is easy to calculate but is not visible, as explained above. Therefore, we must implement a solution that is actually visible in relation to it. To achieve this, we attached rigidly a laser distance meter to the drilling system so that we could establish a relationship between the unitary vector defined by the laser ($V^{\mathbf{U}}_{L1-L2}$), which is visible (observed from one of the topographic stations), and the perforation vector ($V^{\mathbf{U}}_{T1-T2}$). To define vector ($V^{\mathbf{U}}_{L1-L2}$), it is sufficient to measure the emission point of the laser (L_1) and any point on its trajectory (L_2) (Fig. 1).

Designing a system to control the direction of the drill by determining the relationship between these two vectors seems to be possible. However, two problems remain: the gaps in the system and the gravitational fall. To fully understand the geometry of the entire system while taking all factors into account, we constructed a calibration platform for the implemented system. This calibration platform consisted of a 12 m-long (equivalent to the width of the bridge), 1 m-high, 0.5 m-wide wall (Fig. 2).

According to the description above, we must know the coordinates of the ends points in the drilling system and two other points in the laser-guidance system to obtain the two vectors. To determine these coordinates, we can simply drill any hole in the calibration wall; the measurements of this drill hole will inform us about the behavior of the drilling system (Fig. 2). Observing the four points (T_1, T_2, L_1, and L_2) from the topographic stations is simple and guarantees that the four points will be measured in the same spatial coordinate system (Fig. 1).

The length of the drill hole (λ) is simply obtained using Eq. (1):

$$\lambda = \sqrt{(X_{T2} - X_{T1})^2 + (Y_{T2} - Y_{T1})^2 + (Z_{T2} - Z_{T1})^2} \quad (1)$$

where

$T_1(X_{T1}, Y_{T1}, Z_{T1})$ are the coordinates of the entry point of the drill and

$T_2(X_{T2}, Y_{T2}, Z_{T2})$ are the coordinates of the exit point of the drill.

Therefore, the unitary drilling vector defined by both points ($V^{\mathbf{U}}_{T1-T2}$), is given by Eq. (2):

$$V^{\mathbf{U}}_{T1-T2} = \frac{1}{\sqrt{(X_{T2} - X_{T1})^2 + (Y_{T2} - Y_{T1})^2 + (Z_{T2} - Z_{T1})^2}} \times \begin{bmatrix} (X_{T2} - X_{T1}) \\ (Y_{T2} - Y_{T1}) \\ (Z_{T2} - Z_{T1}) \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} (X_{T2} - X_{T1}) \\ (Y_{T2} - Y_{T1}) \\ (Z_{T2} - Z_{T1}) \end{bmatrix} = \begin{bmatrix} (X_{T2} - X_{T1})^{\mathbf{U}} \\ (Y_{T2} - Y_{T1})^{\mathbf{U}} \\ (Z_{T2} - Z_{T1})^{\mathbf{U}} \end{bmatrix} \quad (2)$$

We can calculate this vector for the calibration position (c) on the wall ($V^{\mathbf{U}\,c}_{T1-T2}$) using the measured coordinates of the entry and exit points. We do also for any future position (i) on the bridge using the coordinates of the predetermined points on it ($V^{\mathbf{U}\,i}_{T1-T2}$). If the laser is rigidly attached to the drill and the drilling system has a stable behavior, the relationship between the two vectors then consists simply of a rotation matrix. For any perforation position

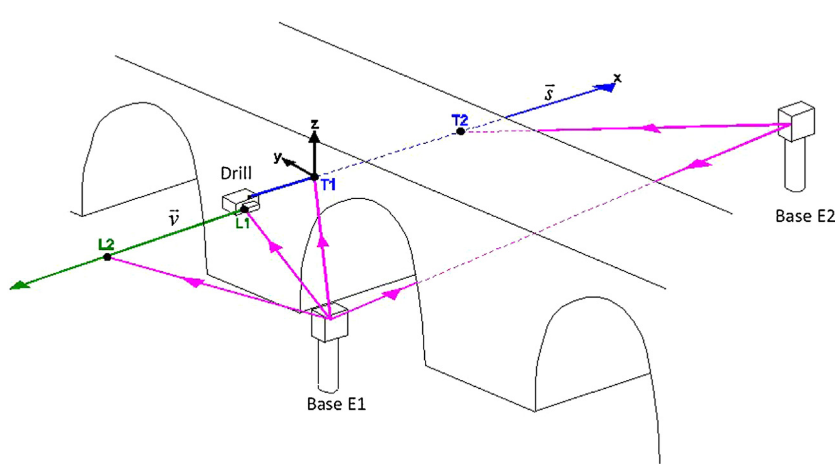

Fig. 1. General diagram of the system.