Construction and Building Materials 150 (2017) 916–931

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of the response of a vaulted masonry structure to differential settlements using point cloud data and limit analyses

Sinan Acikgoz [a,*], Kenichi Soga [b], Jim Woodhams [c]

[a] Cambridge Centre for Smart Infrastructure and Construction, University of Cambridge, Cambridge, UK
[b] Department of Civil and Environmental Engineering, University of California, Berkeley, CA, United States
[c] Topcon Smart Infrastructure Business, Tokyo, Japan

HIGHLIGHTS

- Response of masonry vaulted structures to ground-induced settlements is examined.
- Algorithms proposed to obtain continuous 3D displacement fields from point clouds.
- Data from a settling masonry vault in London Bridge Station validates the algorithms.
- Limit analyses describe settlement response of the vault with accuracy.
- A new technique to predict support movement induced damage is proposed.

ARTICLE INFO

Article history:
Received 26 December 2016
Received in revised form 28 April 2017
Accepted 6 May 2017
Available online 27 June 2017

Keywords:
Masonry vault
Masonry arch bridge
Damage assessment
Laser scanning
Point cloud processing
Cloud comparison
Limit analysis
Settlement

ABSTRACT

Differential settlements have adverse effects on the serviceability and stability of vaulted masonry structures. However, the existing monitoring and assessment techniques do not capture these effects in sufficient detail. In this paper, a new approach is proposed to better describe the influence of support movements on barrel vaults. In this approach, laser scan point clouds of a settling vaulted structure are compared. Different cloud comparison methods are used to accurately identify the displacements of small point cloud segments. In particular, a new cloud comparison method, which modifies the well-known iterative closest point (ICP) registration algorithm, is developed. By constraining ICP to ensure displacement continuity between adjoining point cloud segments, three dimensional movement estimates of the structure are obtained. These estimates delineate the settlement response by indicating the location and magnitude of cracking. This rich information is then used to identify the settlement response mechanism of the vault using limit state numerical analysis. Finally, by interpreting the numerical results with relevant serviceability criteria, a new method to quantify the influence of settlements on barrel vaulted masonry structures is proposed. This damage assessment technique is used to evaluate observed damage due to piling-induced settlements in a masonry viaduct at London Bridge Station.

1. Introduction

A major reason for differential settlements in urban areas is nearby underground construction works [1,2]. As excavation works are carried out, settlements and horizontal movements of nearby structures are inevitable. As a result, the differential movements in abutments, piers and foundations are a recurring problem for vaulted masonry structures [3–9]. These movements can threaten the structures' serviceability and stability and they need to be controlled.

Of particular concern are the serviceability issues, which arise as a result of differential movements. For instance, in masonry railway viaducts, differential settlements of piers may result in track deformations, causing changes in cant, twist and vertical alignment. It is important to measure and/or predict the displacement response at many locations in the vault to infer these movements. More generally, support movements may cause the formation of mechanisms in masonry vaults, which result in cracking. These cracks may deteriorate over time, due to environmental [10] and mechanical effects, such as fatigue and creep [11]. Therefore it is

---

[*] Corresponding author at: Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK.

E-mail address: msa44@cam.ac.uk (S. Acikgoz).

http://dx.doi.org/10.1016/j.conbuildmat.2017.05.075
0950-0618/© 2017 The Authors. Published by Elsevier Ltd.

essential to quantify the location and magnitude of settlement-induced cracking.

Commonly used monitoring techniques provide limited understanding of structural response to settlements. Monitoring is achieved by tracking the absolute displacements of a number of discrete targets on the structure with total stations. Engineers use differential measurements between these sparsely placed targets to correlate the observed movements to damage levels [2,12]. However, as observed in a recent study, it remains difficult to reliably relate displacement signals from a few monitoring targets to serviceability limits or damage [13]. To quantify the influence of settlements, it is necessary to have a more detailed description of the displacement response of the vault.

The currently available settlement induced damage assessment techniques can be improved to become more reliable for vaulted structures. The assessment of settlement induced damage is often performed on the basis of highly uncertain estimates of ground movements. Further uncertainty and errors are introduced with the simplification of the mechanical representation of structures [14]. For instance, complex structures are typically represented with elastic beams and the damage in these models is quantified with semi-empirical techniques, which correlate the observed tensile strains to the magnitude and extent of cracking [1,2]. While these assessment tools may be effective for simple facades and framed buildings, it is shown in this study that they do not capture the mechanical behaviour of more complex vaulted masonry structures.

To overcome these challenges, alternative approaches for monitoring and assessing settlement-induced damage in masonry vaulted structures are proposed in this study. Primarily, this entails a new monitoring technique, which utilises several laser scan point clouds of the structure, collected during ground works. The point cloud data is processed with a range of techniques including primitive shape fitting [15], cloud-cloud distance comparison [16] and rigid body cloud registration [17] to infer displacements from point clouds. With this approach, instead of measuring the displacement of a few discrete points on the structure, 3D displacements of all visible surfaces on the intrados of the arch can be obtained. Then, by using this information, it is possible to track the rotation and lateral displacement of piers as well as continuous longitudinal and transverse displacement profiles of the arch barrel. This rich information allows a conservative estimation of emerging crack opening and track displacement parameters, which are useful for determining the serviceability of the investigated structure. The displacement data is also useful for investigating the accuracy of simple modelling tools, which may be used in lieu of the aforementioned beam methods to capture the settlement response behaviour. For this purpose, the paper examines the accuracy of a simple limit analysis based damage assessment approach. The utility of this modelling approach for providing a preliminary damage assessment for a given support settlement is also explored.

The paper is organised as follows. First, a case study from the London Bridge Station redevelopment project, is described in Section 2 to introduce the current techniques of monitoring and assessing settlement-induced damage and discuss their shortcomings. Then, a new monitoring technique, which utilises point clouds, is developed in Section 3. For the development, the accuracy of established methods of cloud comparison and registration techniques are evaluated, highlighting the difficulties in estimating accurate displacements using these methods. Suitable modifications to these techniques are then proposed to develop point cloud data processing algorithms which provide continuous 3D deformation profiles. Such information is particularly useful for estimating damage due to movements. On the basis of these results, new mechanical models for damage assessment are proposed in Section 4. These models are based on limit analyses of masonry arches and provide direct indicators of damage. Finally, upon validating these models with point cloud data, new damage assessment maps are proposed for settlement-induced damage in vaulted masonry structures in Section 5.

2. The case study

London Bridge Station is a historic railway station composed of a series of brick-built viaducts, originally constructed in various phases during the 19th century. As a part of the recent redevelopment works involving removal and replacement of sections of the viaducts, new piles were constructed in these viaducts, whilst the tracks above remained operational. The piles formed the foundation of buttress walls, which were constructed later. These buttress walls were designed to take the thrust from neighbouring barrel vaults after the demolition of a part of the masonry viaduct for the construction of the new station. This sequence of construction is schematically illustrated in Fig. 1a. The critical investigation phase which caused significant settlements is the piling phase, Phase 1. The piles were constructed in Arch E55 but this case study will examine the neighbouring Arch E57, which was not demolished.

The location and construction sequence of piles is illustrated in Fig. 1b. All piles were 0.45 m in diameter, 25 m in length and were constructed using a segmental flight auger. The construction of piles started on 31.01.13 from the north and progressed towards the south. Piling works finished on 16.08.13. In this period, 105 piles were constructed. Construction of buttress walls followed shortly after, and was completed before 21.11.13.

Fig. 2 illustrates the internal construction of the examined Arch E57 with a longitudinal section view. The barrel vault has a square span of 9.6 m and a rise of 2.2 m. The multi-ring arch is well-bonded and is 0.7 m thick. It is supported by 1.6 m thick piers of solid brick. Above the piers is 1.9 m backing and 1.4 m well-compacted soil fill, which together support the track ballast. It is noteworthy that a bitumen waterproofing layer exists between the fill and the backing, which is designed to divert the draining water to discharge from the piers. The piers themselves are supported on shallow foundations of lime concrete, which bear onto alluvial ground.

The plan view in Fig. 3a shows that Arch E57 has a width of 27 m. Two cross-passages allow access to the neighbouring arches and are located centrally. Fig. 3a also highlights six longitudinal sections, shown with dashed lines, where monitoring targets were placed. Two of the six longitudinal sections monitored with total stations are highlighted. The one in the north is labelled L1 and the one in the south is labelled L2. In addition, T1, a transverse section of the bridge, running along its crown, is also highlighted.

In each longitudinal section, monitoring targets were placed at the eastern and western springing points and the crown. Monitoring results for the section L1 are demonstrated with vector plots in Fig. 3b, where the lateral and vertical movements in the longitudinal plane are respectively denoted by ΔX and ΔZ. The transverse deflections ΔY are not reported, as they were negligible. The top row of Fig. 3b shows the recorded movements of targets (in mm) on 05.03.13, by which time 50% of the piles in Arch E57 had been constructed. The bottom row shows the recorded movements on 23.11.13, after the construction works finished. As expected, significant vertical settlements are observed on the western side for both dates. This movement is accompanied by considerable lateral movement of the pier top. However, negligible movement is observed on the eastern springing.

The monitoring data in Fig. 3b is analysed further in Table 1. In this table, the differential vertical settlement of piers (denoted by Δp_v) and the span change due to differential lateral movements (denoted by Δp_h) are reported. The results from L1 and L2 are