Terrestrial laser scanning for the monitoring of bridge load tests – two case studies

H. Lõhmus, A. Ellmann, S. Märdla & S. Idnurm

To cite this article: H. Lõhmus, A. Ellmann, S. Märdla & S. Idnurm (2017): Terrestrial laser scanning for the monitoring of bridge load tests – two case studies, Survey Review, DOI: 10.1080/00396265.2016.1266117

To link to this article: http://dx.doi.org/10.1080/00396265.2016.1266117

Published online: 19 Apr 2017.

Submit your article to this journal

Article views: 12

View related articles

View Crossmark data
Terrestrial laser scanning for the monitoring of bridge load tests – two case studies

H. Lõhmus*1,2, A. Ellmann2, S. Märdla2 and S. Idnurm2

Terrestrial laser scanning (TLS) technology has various applications due to its capability of acquiring detailed 3D information about objects within a limited time-period. Yet, it is not widely used for the deformation monitoring of structures. To investigate the suitability of TLS for such tasks, a time-of-flight type Leica ScanStation C10 was used to determine the vertical deformations for two bridge load tests in Estonia, namely for the Loobu highway bridge and the Tartu railway overpass. The TLS results were verified with precise levelling, reflectorless tacheometry and dial gauges. Generally, deformation estimates obtained from TLS and other measurement techniques show sub-millimetre agreements (in terms of standard deviations). The maximum differences between the TLS and precise levelling results were 3.4 and 0.8 mm for the Loobu and the Tartu study, respectively. Since TLS has not yet reached the same accuracy as conventional geodetic high-precision techniques, it cannot fully replace them in high accuracy applications. However, TLS can be considered a complementary survey method for load tests as it provides valuable entire surface covering 3D information.

Keywords: Point cloud modelling, Low-pass data filtering, Precise levelling, Laser tacheometry, Dial gauges, Load testing, Deformation monitoring

Introduction

Terrestrial laser scanning (TLS) is a state-of-the-art measurement technology with a capability of acquiring high-resolution 3D point clouds of objects in a short time. Its applications include heritage mapping, volume calculations, as-built surveys of buildings, topographic surveying, data gathering of complex objects for 3D modelling etc. However, the TLS technology is not widely used for the deformation monitoring of structures. The main hindrances have been the insufficient knowledge of the accuracy of TLS data, the complexity of the processing of TLS data, the high cost of TLS equipment and the TLS data processing software. Some earlier attempts in the use of TLS for determining the deformations of structural elements have been reported by Park et al. (2007), Rönnholm et al. (2009) and Gordon and Lichti (2007). These studies monitored structures in laboratory conditions where the errors due to external influences can be controlled.

In contrast, this study explores aspects of TLS point cloud modelling and its applicability for determining vertical deformations for bridge load tests in a non-laboratory environment. Even though the accuracy of an individual TLS survey point may be relatively poor for determining deformations (2–50 mm, depending on the scanner used), modelling of the entire point cloud can provide an effective and accurate description of the behaviour of a construction (Gordon et al. 2004). Also, Meng et al. (2014) reported achieving 2 and 3 mm accuracy in determining railway track positions by TLS in the horizontal and vertical plane, respectively, that could be used for precise 3D deformation identification.

Implementations of TLS technology for bridge load tests have been previously reported by Zogg and Ingen-sand (2008), Lovas et al. (2008) and Mill et al. (2015). These studies, similarly to the present one, involve static loading (cf. section ‘Bridge load tests’), whereas Truong-Hong and Laefer (2014) investigated the use of TLS to determine vertical bridge displacements during dynamic loading. The determination of the bridge deformations in these studies relied upon comparisons of TLS point clouds, where at least one of the point clouds was modelled as a (reference) surface. This is usually conducted by commercial software, which utilises ‘black box’ algorithms, thus the modelling parametrisation is limited. The present contribution describes the point cloud modelling and the deformation determination procedures more thoroughly. The current study also confirms that a modelled surface offers more representative information on bridge deformations than an unmodelled TLS point cloud.

The outline of the paper is as follows. First, the main purposes and different types of bridge load tests are explained. Thereafter the principles of determining deformations that occur during a load test are reviewed. This is followed by a description of two case studies. Subsequent sections give an overview of the used measurement and data processing methodologies, analyse the achieved...
results and comparisons of TLS-based results with conventional surveying techniques. A brief summary concludes the paper.

**Bridge load tests**

Generally, the load testing of bridges is performed to determine the carrying capacity of the structure, which could be affected by ageing, weather and traffic. Bridge load testing is necessary after visually detecting noticeable damages to bridges or in other circumstances that lead to suspicions about the safety of bridges, e.g. due to a significant rise in traffic. Also, after a bridge has been constructed, it is quite common to conduct a load test to prove that the bridge can, in fact, carry the expected load. Bridges can be tested using static or/and dynamic loading. For static load testing (depending on the expected outcome) heavy vehicles (dumper trucks, army tanks, locomotives etc.) or other heavy items (metal blocks, sand bags etc.) are placed on the bridge deck. Displacements, deformations (strains) and the formation of cracks in the structure are monitored both visually and instrumentally during the test.

There are three types of static load tests: (1) supplementary, (2) proving and (3) destructive load tests (Ryall 2001). Supplementary tests are the most common since the load used exceeds neither the actual nor the theoretical carrying capacity of the bridge. Usually, the load reaches only 70% of the design load (Idnurm 2013), therefore not causing damage to or a collapse of the bridge. Thus, supplementary load testing is also safe for the testing team. The measured deformation values are compared with the pre-calculated values to determine whether the selected calculation method was appropriate.

A proving load test involves applying loads incrementally up to a value equivalent to the ultimate limit state of the bridge and is, in a way, an extension of the supplementary load test (Ryall 2001). Although it provides direct proof of the actual carrying capacity, there is always a danger of the bridge becoming permanently damaged during such a test. Since the bridge behaviour is monitored by stress and deflection measurements as the test progresses, it would be possible to estimate behavioural trends. Any critical values of deformations, unexpectedly sudden increases or non-linearities may indicate imminent failure (Fig. 1) and the test must be halted, thereby preventing a collapse of the bridge.

Destructive load testing is used rarely – mainly on old bridges which are to be taken out of service and subsequently demolished during or after the testing. It is also practised on bridges that have deteriorated beyond economic repair (Ryall 2001). The main goal of destructive tests is to estimate the conditions of similar bridges elsewhere. For various reasons, the actual carrying capacity obtained from such tests often proves to be (much) larger than pre-calculated estimates.

Dynamic load tests provide information about dynamic behaviour of the bridge constructions such as displacements, deformations, natural frequencies, damping and mode shape [a constructional characteristic (co-effect of inertia and rigidity) that describes the shape of an object at a specific resonance frequency]. During dynamic testing, typically one or more multi-axial vehicles with specific weight manoeuvre on the bridge at various speeds. Owing to vibrations and possible resonance, the dynamic loading is considered more hazardous, as this may lead to more extensive damages. Dynamic load testing is rarely used for short bridges. A more thorough overview of bridge load testing can be found in Ryall (2001), UK’s Institution of Civil Engineers (1998) and Bungey and Millard (1996).

**Determining deformations of a bridge**

Several devices are used for the determination of different types of structural deformations, such as strain gauges, dial gauges, inclinometers, crack microscopes, rulers and callipers. Geodetic instruments include precise levelling instruments, total stations, terrestrial laser scanners, terrestrial photogrammetric instruments and survey grade GNSS (Global Navigation Satellite System) devices. So far, determining bridge deformations has mainly been carried out by spatially low-resolution (point-wise) observing techniques such as precise levelling, tacheometry and dial gauges. Data processing has thus been straightforward and relatively simple.

In contrast, TLS provides a high-resolution 3D point cloud of the structure. However, individual points of the point clouds cannot be compared directly as the same points of the surface are not recognisable in different scans unless there are special targets that can be identified by a special software. A direct cloud-to-cloud deformation calculation method would be the fastest as it does not require gridding or meshing of the data, nor calculation of surface normals (Girardeau-Montaut et al. 2005). However, this method presently appears to be under-researched and not widely used.

Since there is a very small probability that the points surveyed in different scans would fall onto the same locations of the investigated surface, the calculation of a deformation in a specific point of interest requires assumptions (e.g. in a relatively small area the deformation differences are minimal) and/or modifications (similar to modelling) of the original point cloud. This suggests that, in any case, the deformation determination is actually carried out by modelled surfaces rather than individual points. However, not all point clouds of the different scan epochs need to be modelled – one reference surface is required while all other point clouds can then be compared to the reference surface.
Generally, point cloud modelling is a complicated task (Tsakiri et al. 2006) as the TLS measured points are not organised (i.e. points are distributed evenly only in the angular domain so that the points reside on the measured object as laser beam stripes that spread out when moving away from the scanner), noisy and the surface can be arbitrary, with unknown topological type. Thus, surface model creation algorithms must infer the correct geometry and features (e.g. break lines, edges, apexes etc.) of an object of interest.

There are numerous surface modelling methods. A thorough overview of the methods, including common modelling and visualisation terms and software packages can be found in Remondino (2003), for example. Most surface reconstruction methods can be categorised as explicit or implicit methods (Rathore and Gupta 2014). Explicit methods are mainly local geometric approaches based on dual Voronoi diagrams and Delaunay triangulation, such as the α-shape and Crust algorithms (Rathore and Gupta 2014). Implicit methods attempt to determine a smooth surface function that passes through all positions where the implicit function reaches some specific value (usually zero) (Gotsman and Keren 1998).

Many of the surface reconstruction software perform triangulations, which convert the given set of points into a consistent polygonal model (mesh) (Edelsbrunner 2001). This operation divides the input data into simplices and usually generates vertices, edges and faces that represent the surface. The triangulation can be performed in 2D (e.g. Delaunay triangulation, triangulated irregular network TIN), 2.5D using DDT (data dependent triangulations) or in 3D, based on the local properties of the points defined in 3D (Tsakiri et al. 2006).

Further, since the raw point cloud consists of noisy data, it is essential to filter it for precise surface reconstruction. Various algorithms are suitable for point clouds with noise, such as Radial Basis Functions (e.g. Carr et al. 2003), the Ball-Pivoting Algorithm (e.g. Bernardini et al. 1999), the Power Crust (e.g. Mederos et al. 2005) etc. Another method for noise reduction is low-pass filtering which enables to eliminate large errors in the original cloud and create a continuous smooth surface model. According to Chen (1989), for a point \((x_0, y_0)\) on the surface of a TIN, its filtered elevation \(z_f(x_0, y_0)\) is an average of the elevations of its neighbouring points:

\[
    z_f(x_0, y_0) = \frac{1}{N} \sum_{k=1}^{N} z_k \quad (k = 1, \ldots, N),
\]

where \(z_k\) denotes the elevation of the \(k\)th neighbouring point and \(N\) the number of neighbouring points involved. The range inside of which neighbouring points are searched can be \((i)\) a circle with its centre at the point or \((ii)\) a square with its intersection of the diagonals at the point, and its radius or side length defined by the user. The larger the radius or side length, the more details will be omitted and, consequently, the smoother surface will be created. In the present study, such a low-pass filtering approach was applied for the surface compilation and for obtaining the deformation estimates from the TLS deformation mesh (cf. sections ‘Meshing and TLS-based deformation calculation’ and ‘Comparison of the TLS results with those of precise levelling, reflectorless tacheometry and dial gauges’). A sample of the outcome of the applied filtering approach is illustrated in Fig. 6.

At present, the solitary use of TLS technology is regarded with caution for such important tasks as deformation monitoring. In order to confirm and increase the reliability of TLS-based results, additional measurements with a more accurate geodetic instrument – a levelling instrument or a total station, are usually involved. To further investigate the capabilities and shortcomings of TLS and subsequent data processing methods, the technology was applied to two case studies of determining vertical deformations during static bridge load tests conducted by the Department of Road Engineering of Tallinn University of Technology (TUT) in 2013. The emphasis of the study is on the geodetic aspects of bridge test monitoring and data modelling. Thus, only the relevant characteristics of the bridge structure will be explained in the following text.

Tested bridges

Loobu highway bridge

The first bridge load test took place on 14 April 2013 at the Loobu highway bridge built in 1953. It is located in Estonia, on the 66th kilometre of the European route E20 that connects the capital Tallinn and the city of Narva. A destructive bridge load test was carried out by a total load of 200 t [100 pieces of special 2 t cast iron blocks; \(1 \times 1\) (metric) tonne = 1000 kg] asymmetrically placed on to the Southern side of the bridge deck (Fig. 2).

Three loading epochs were applied to the bridge during the course of the test. In the first epoch, the bridge was loaded with 80 t. Since the detected deformations turned out to be significantly (approximately 2.8 times) lower than the pre-calculated values, it was decided to place an additional 84 t onto the bridge. In the final epoch, the load was raised to 200 t. The bridge was designed for an ultimate allowable load of 60 t. The maximum deformation at 200 t load was pre-calculated as 50.3 mm, whereas the actual measurements showed a maximum deformation of only 35.4 mm.

The Loobu bridge structure and the specifics of the placement of load, including preliminary calculations, can be found in Mill et al. (2015) and Idnurm et al. (2013), and are not duplicated here. Even though a part of the bridge test results have already been reported by Mill et al. (2015), the present contribution provides a more complete verification of the TLS results. In particular, the present study also involves the total station data sets and accounts for the across-bridge torsion, which were omitted in Mill et al. (2015).

Tartu railway overpass

The second (supplementary) load test took place on 8 June 2013 at the newly constructed railway overpass in the city of Tartu (second largest city in Estonia). The three-span overpass consists of two 2 m wide reinforced concrete beams, separated by a narrow joint. A 6-axle diesel locomotive GE C36-7i (with a maximum load of 177 t and the average axle load of 29.5 t) was used as a static load, cf. Fig. 3. The test was carried out in two epochs (Idnurm 2013). In epoch I the heaviest section of the load was positioned on the middle span and in epoch II on the Southern span of the overpass, accordingly to Fig. 5. In both epochs the locomotive was stationary for an hour.
Before the loading, a TLS survey was executed to determine the initial geometrical shape of the bottom of the overpass. During the course of epoch I, the deformed shape of the bottom of the middle span was scanned. Precise levelling and laser tacheometry were used for detecting the vertical deformations of the bridge deck and the Eastern side of the beam, whereas dial gauges were used to monitor the deformations of the bottom of the Southern and the middle span of the overpass (Figs. 4 and 5). The measurements revealed deformations up to 6.4 mm.

Measurement methodologies

Precise levelling

During both load tests, the bridge deformations were primarily determined by precise levelling, more specifically by the intermediate sight method. A precise digital level Trimble DiNi03 with two calibrated bar coded invar levelling staffs was used. According to the manufacturer’s specifications, the instrument’s standard deviation is 0.3 mm per 1 km of double-run levelling conducted using invar staffs. Before the loading, the horizontality of the level’s line of sight was checked by the Näbauer method (cf. Trimble Navigation Ltd 2007). The measured collimation error was recorded and used as a correction for the levelling results. The levelling marks were firmly attached to the bridge. A steel rod embedded in stable soil nearby was used as a temporary reference benchmark for defining and checking (after each set of measurements) the height of the instrument’s horizon.

Reflectorless tacheometry

During the Loobu load test, reflectorless total stations Trimble S6 and Trimble M3 were used. For
According to the manufacturer, the angle and distance measurement accuracy in DR (Direct Reflex) mode is 2′′ and 2 mm, and 2′′ and 3 mm for the S6 and M3, respectively. To determine deformations, each tacheometry mark was measured with one arc.

4 Cross-section of the Tartu railway overpass and locations of the survey marks (see the legend). Units in millimetres. (modified from Idnurm 2013, courtesy of J. Idnurm)

5 Locations of the measurement stations, survey marks, reference points and the load (locomotive) at the Tartu overpass load testing. Blue dashed lines denote the supporting structures (piers, abutments, beams) of the overpass, whereas the vertical red lines denote the joints separating the three independent bridge spans. A horizontal red line separates the two adjacent bridge beams which support one railway track (see also Fig. 4)
of face left and face right observations in DR distance measurement mode during each load epoch (including the zero-load epoch). Marked points on the sides of the bridge beams were used as the tacheometry targets.

**Dial gauges**

In the Tartu bridge load test dial gauges were used in addition to the two aforementioned measurement techniques. Their wires were attached to the bottom surface...
of the bridge beams at ¼, ½ and ¾ lengths of the Southern and middle bridge spans (see Fig. 11). The dial gauges used have a reading resolution of 0.01 mm.

**Terrestrial laser scanning**

A time-of-flight (TOF) type TLS Leica ScanStation C10, equipped with a dual-axis compensator, was used for the scanning. According to the manufacturer, the accuracy of a single scan point position and a modelled surface is 6 and 2 mm (standard deviation, one sigma), respectively, within a range of 1–50 m. In the current study the maximum distances between the scanner and the object were approximately 21.5 and 9.5 m for the Loobu and Tartu tests, respectively.

Different TLS devices have very different performances and suit different applications. For instance, phase shift (PS) scanners are better suited for short distances (typically under 100 m), whereas TOF scanners may provide good results beyond 200 m and even further. Additionally, PS scanners offer higher scanning resolutions and faster scanning rates compared to TOF scanners. Nuttens et al. (2012) concluded that from the compared scanning instruments the PS type TLS Leica HDS6100 was the best suited for tunnel deformation measurements. However, the intention of this research was not to compare the performance of different TLS scanners. The Leica ScanStation C10 was the only scanner used for the present study.

**TLS survey and data post-processing**

The TLS survey and the corresponding data post-processing featured the following stages:

1. scanning the original geometrical shape of the bridge before loading,
2. scanning the deformed shape of the bridge at specific loads,
3. registration (transformation) of individual scans into a common coordinate system,
4. removing noise and irrelevant objects from the measured point cloud,
5. data thinning,
6. creating surface meshes,
7. subtracting the zero-load epoch mesh from the respective load epoch meshes.

**Registration (transformation) of TLS point clouds**

The alignment of the scans was conducted by target-to-target registration. Even though the scanner remained in the same location for the duration of the entire test at both load tests, the scanner was reoriented before each loading epoch (including zero-load) using Leica 3° × 3° HDS (High Definition Surveying) targets mounted near the bridge. This enabled to check the stability of the scanner station, thus ensuring a higher scanning accuracy. The centre of the stable targets was determined automatically from separate high-density target scans. Four and two targets were used at Loobu and Tartu bridge tests, respectively. The point cloud registration was carried out with the commercial Leica Cyclone software using the same set of targets. The registration errors for the vertical positions of the targets in both load tests remained below 1.0 mm. This confirms the stability of the scanner during the measurements.

**Meshing and TLS-based deformation calculation**

The standard ‘griddata’ function of the engineering software MATLAB (cf. The MathWorks, Inc. 2001) was applied for the creation of surface meshes from the registered point clouds. A default linear interpolation method was used in the present study. It is based on a Delaunay triangulation which ensures that no vertex lies within the interior of any of the circumcircles of the triangles in the network. A surface reconstructed by the ‘griddata’ function always passes through the grid specified by the rectangular coordinates.

The rectangular coordinates of the grid nodes were defined by the MATLAB ‘linspace’ function. A 1 × 1 cm grid was first considered for the surface reconstruction and it remained so in the Loobu case. For the Tartu point clouds, this grid step appeared not to be optimal, as the Tartu point clouds were excessively noisy (forming vertically nearly a 1 cm ‘thick’ layer in the middle of the bridge beam (Fig. 6a)), hence the constructed (1 × 1 cm) meshes become unrealistically ‘bumpy’ (Fig. 6b). To reduce the possibly adverse effect of the noisy data on the quality of the subsequent deformation calculation, a sparser grid step was required. To achieve a smoother surface model a low-pass filtering technique was applied [see equation (1)] for forming grids with various step sizes. A 5 × 5 cm grid yielded acceptable results (Fig. 6c) and was chosen for the surface modelling for the Tartu bridge. Grid steps other than 5 × 5 cm were also tested but did not yield better results.

To determine the expected precision of the modelled surfaces, a MATLAB script calculating the perpendicular distance between each point of the initial TLS point cloud and the constructed surface model was created. The distributions of the separations of individual TLS points with respect to the modelled surface (along the surface normal) were determined for each case (i.e., both bridges and each scanning epoch). The mean standard deviation of such separations was calculated to be 1.0 and 1.1 mm for the Loobu and Tartu bridge, respectively. These values are nearly two times better than the manufacturer’s 2 mm (one sigma) estimate for the modelled surface accuracy (Leica Geosystems 2016) for the data acquired by the scanner (Leica ScanStation C10) used in this study.

For example, the spatial distribution of the separations between the modelled surface and the individual TLS points of the Tartu railway overpass in epoch I are shown in Fig. 7. The corresponding histogram demonstrates a normal distribution of the separations, (Fig. 8). Note that about 95% of the separations are within ±1 mm while only the beam edge points appear to be further than ±2 mm from the model.

It should be noted that the influence of external errors (see e.g. Wang et al. 2016) on TLS results was not modelled in this study since all scans were executed on the same object under similar environmental and measurement conditions. Recall that all of the scans were acquired from exactly the same instrument location and the same (stable) targets were used for registration (cf. section ‘Registration (transformation) of TLS point clouds’). Also, the weather conditions were rather stable during the tests (e.g., the air temperature varied from 3° to 4° and 21° to 22° Celsius during the Loobu and Tartu tests, respectively).
Typical external error sources include the laser beam wander, atmospheric refraction and critical incidence angle (Wang et al. 2016). An incidence angle nearing 90° may cause signal deterioration, negatively affecting the precision of the distance determination. One needs to account for possible instrumental errors, in particular, for axis orthogonality errors that increase for TLS points close to the zenith. Nevertheless, due to the same scanning location in practically unchanging weather conditions the influence of such errors would be of roughly equal magnitude for all scans. Consequently, these error sources would be reduced by differencing of the results of sequential scans. Instead, we created meshes of zero-load and consequent load epochs (e.g. with a closest point technique, Girardeau-Montaut et al. 2013), however, the result would be directly dependent on the noise level and the point density of the different scans. Instead, we created meshes of zero-load and consequent load epochs and arithmetically subtracted these from each other. Such meshing allowed to fill the gaps in the point cloud data caused by the low scanning resolution and the obstacles between the bridge beams and the scanner. Besides, it reduced spikes and noise in the point cloud resulting in smoother and cleaner data (Fig. 6). The point clouds of the Loobu and Tartu scans were modelled as 1 × 1 and 5 × 5 cm meshes, respectively. Note that a larger grid step was used in the Tartu case due to noisier TLS data (section ‘Meshing and TLS-based deformation calculation’).

The Loobu (Fig. 9) and Tartu (Fig. 10) test results revealed that TLS-determined deformations can be relatively noisy, especially near the bridge supports (i.e. the Loobu bridge, (cf. Fig. 9)]. The artefact (abnormal fanlike stripes) at approximately 22 to 23 m along the Tartu bridge (Figs. 7 and 10b) could be a peculiarity of the scanning technology rather than an extraordinary deformation of the bridge. In particular, this could be due to the scanning station being located exactly below that area (i.e. in the nadir). Recall that the scanner rotates around its vertical axis to gather survey data that spread out fanlike when moving away from the scanner.

There was also a high level of noise in the middle of the Tartu bridge span (Fig. 10). It is due to the fact that the scanner was able to acquire data from the narrow joint between two adjacent bridge beams (Fig. 11). This joint (gap) between the two bridge beams does not adequately reflect the behaviour of the structure under static loading (confirmable by visual inspection). However, the noise was not completely removed during the cleaning of the point cloud as it would have required a disproportionately large effort (either for devising a special algorithm for automatic removal or executing a rather time-consuming manual removal of the residual noise) for a relatively small gain. Additionally, such a cleaning process could have had an adverse effect on the results by unintentionally removing quality points nearby. Regardless, this excessively noisy area of the bridge was excluded from the comparisons of TLS-based deformation values with the ones obtained by alternative measurement techniques (section ‘Comparison of the TLS results with those of precise levelling, reflectorless tacheometry and dial gauges’).

### TLS-determined deformations

The calculation of the deformations could have been carried out directly from the point clouds of different loading epochs (e.g. with a closest point technique, Girardeau-Montaut et al. 2005 and Lague et al. 2013), however, the result would be directly dependent on the noise level and the point density of the different scans. Instead, we created meshes of zero-load and consequent load epochs and arithmetically subtracted these from each other. Such meshing allowed to fill the gaps in the point cloud data caused by the low scanning resolution and the obstacles between the bridge beams and the scanner. Besides, it reduced spikes and noise in the point cloud resulting in smoother and ‘cleaner’ data (Fig. 6). The point clouds of the Loobu and Tartu scans were modelled as 1 × 1 and 5 × 5 cm meshes, respectively. Note that a larger grid step was used in the Tartu case due to noisier TLS data (section ‘Meshing and TLS-based deformation calculation’).

### Comparison of the TLS results with those of precise levelling, reflectorless tacheometry and dial gauges

Regardless of the high surface modelling accuracies (section ‘Meshing and TLS-based deformation calculation’), the constructed surface models still appeared to be reasonably ‘bumpy’ (Fig. 6b and c) as opposed to the actual surface of the bridge beam. This is probably due to the measurement noise associated with TLS as its individual point accuracy proves to be insufficient for precise modelling. Therefore, to acquire adequate deformations from the TLS measurements for comparison with conventional point-wise methods, a TLS estimate in a specific point of interest was not obtained from a single (possibly
erroneous) cell of the deformation mesh but was calculated as an average of the surrounding (neighbouring) cells [see equation (1)].

It is important to note that for both load tests, precise levelling was used to detect the deformations of the bridge deck, whereas other measurement techniques monitored the deformations of the bridge beams (TLS and dial gauges for the bottom surface of the bridge beam and tachometry for the side of the bridge beam). A direct verification of TLS results could only be executed with dial gauges as their mounting wires were clearly detectable from the TLS point cloud (Fig. 11). For the other measurement techniques, the direct determination of the exact locations of the survey marks from the point cloud was impossible. Instead, the TLS deformation estimates were obtained from the middle strip of bridge beam at the longitudinal distance of the corresponding survey mark. For example, in order to compare the precise levelling and TLS at the Western levelling mark W10 (cf. Fig. 5), a TLS deformation estimate was acquired from the bottom surface in the middle of the Western bridge beam at the longitudinal distance of the mark W10. Consequently, data from the proximity of the bridge joint, the area most contaminated by the measurement noise, was removed from the subsequent comparisons.

The Loobu bridge deformation estimates obtained from TLS and precise levelling differed by up to 3.4 mm, with a standard deviation of 1.6 mm. The TLS-based deformations for the Northern beam were systematically larger (Fig. 12) than those obtained from precise levelling, whereas for the loaded Southern beam they were systematically smaller (Fig. 13). This is due to the following reasons: (i) large incidence angles associated with the TLS measurements (Mill et al. 2015), (ii) eccentric placement of the levelling marks on the bridge deck with respect to the TLS monitored bridge beams, (iii) different deformation behaviour of the bridge deck and the bridge beams, and (iv) the asymmetric placement of the load with respect to the bridge deck and the two beams (see Fig. 9b and Fig. 14).

The graphs in Figs. 12 and 13 suggest that the difference between the levelling and TLS results could be a simple function of the load – the heavier the load, the larger the difference. However, the circumstances are more complex. At the Southern edge the levelling reveals a larger descent than the TLS technique, whereas at the Northern side just the opposite occurs (see Figs. 12 and 13). This can be explained by the behaviour of the bridge deck under the asymmetrically placed static load and the locations of different surveying marks, see Fig. 14.

The static load causes a general (longitudinal) lowering of the bridge deck and its beams below. The load is placed asymmetrically at the Southern edge of the bridge deck, which is a monolithic reinforced concrete slab. Thus, also an across-deck torsion occurs. Therefore, the magnitude of the deformation becomes a function of the
distance from the load and depends on which side of the load the deformation measurements are conducted. The detected discrepancies between the different measuring techniques consist of varying bridge deck/beam deformations at the locations of individual surveying marks. In this particular case the surveying marks to the South of the load go down more than those directly under the load. The surveying marks to the North of the load go down less than those under the load. The Northernmost marks settle the least.

The torsion of the bridge deck caused the Southern levelling marks (located also to the South of the static load) to go down more than the TLS measured Southern bridge beam directly under the load (see Fig. 14), yielding smaller TLS deformation estimates (cf. Fig. 13). With the increase in the load, the across-deck torsion also

10 TLS-determined deformations of the Tartu railway overpass in epoch I (the heaviest section of the eccentric load on the middle span after 20 min, see Fig. 5): a 3D view; b top view; c side view (from the East, the North is in the right-hand side). The spikes are due to measurement noise associated with the narrow gap (joint) in the middle of the span along the bridge. The magenta coloured dot denotes the nadir location of the TLS station, note the abnormal fanlike stripes around it. Black lines depict the bridge piers and the grey line/rectangle the location of the load. Units are in metres

11 Dial gauges, mounted by wires (visible in the point cloud, see the right hand figure) to the Tartu railway overpass reinforced concrete beams (left). Note the longitudinal narrow gap separating the two adjacent bridge beams
increased, leading to larger differences between the TLS and the precise levelling results.

Since the Northern levelling marks were further from the load than the TLS measured bottom section of the Northern beam (Fig. 14), the TLS deformation estimates appeared to be larger (Fig. 12). This also proved to be the case in the comparison of the TLS and the reflectorless tacheometry results (Fig. 15), where the Northern tacheometric marks were more distant from the load than the TLS measured bottom section of the Northern beam (Fig. 14).

The agreement between the Loobu TLS and total station (Figs. 15 and 16) results was slightly better than that with the levelling. The detected discrepancies between TLS and total station surveys reached up to 2.8 mm, but remained mostly below 1.0 mm. The deformation values obtained from those instruments could also be affected by identical noise sources as TLS and total stations share similar measuring principles. Besides, both detected the deformations of the bridge beams whereas the precise levelling measurements investigated the behaviour of the bridge deck.

By depicting the Loobu vertical deformations of all measurement techniques together (Fig. 17), the torsion of the bridge deck caused by the asymmetric placement of the load (with respect to bridge beams/deck) becomes clearer. Figure 17 demonstrates that the discrepancies between the results of the TLS and the other methods are not constant but vary systematically depending on the distance from the load and on which side of the load the measurements are performed. This suggests that the main sources behind the differences in deformations are not measurement technology based (depending on e.g. measurement accuracies of the instruments or TLS data post-processing) but originate from the asymmetric placement of the load. Thus, the actual accuracy of TLS after point cloud modelling could be better than the stated standard deviation of 1.6 mm, maybe even within one millimetre.

In a similar study at the Felsenau viaduct (Zogg and Ingensand 2008), the deformations obtained by TLS and those by precise levelling differed up to 3.5 mm (the maximum deformations of the bridge girder reached 10 mm), whereas the mean residuals for the different loading situations (epochs) differed by up to 0.8 mm.
The TLS-determined deformations of the Tartu bridge were generally (with a few opposite sign exceptions) larger than those obtained from precise levelling (Fig. 18), reflectorless tacheometry (Fig. 19) and dial gauges (Fig. 20). Figures 18–20 show the epoch I test results, for the corresponding locomotive’s position see Fig. 5. The maximum discrepancies reached 1.3 mm. The standard deviation between the TLS and the precise levelling-based deformations was 0.6 mm. However, a comparison of the results of TLS and the other sensors is difficult since in some cases the exact point correspondence could not be established. Please note that only the dial gauge-based deformations were determined for the same locations of the same surfaces as the TLS. However, the verticality and the stability of the dial gauge setup (Fig. 11) is questionable (first, a significant non-verticality of the mounting wires was detected during the TLS data postprocessing, second, the triangular base plates of the dial-gauges were placed on non-compressed soil, third, the behaviour of the mounting wires could have changed.

14 Cross-section of the Loobu highway bridge. Note the locations of the profiles of different survey marks with respect to an asymmetrically placed static load (cast iron blocks). (modified from Mill et al. 2015)

15 Comparison of TLS and reflectorless tacheometry results for the Northern beam of the Loobu bridge. See the legend for the different load cases. P.1 to P.9 denote the longitudinal position of the tacheometry marks on the Northern cantilever beam.
with temperature and sudden variations in wind speed or direction). There were too few common survey marks between TLS and any of the other techniques to give more valid conclusions, but the selected marks show a reasonable agreement (within 1 mm, which matches the TLS modelling accuracy).

Since the discrepancies between the TLS and the dial gauges show a similar pattern to the discrepancies between the TLS and the other methods in the Tartu case, we conclude that they result not from the eccentricity of the survey marks nor the different deformational behaviour of the different bridge constructions, but from the capability and peculiarities (e.g. measurement noise, data post-processing and also fanlike deformation stripes, Fig. 10b) of the TLS technology.

**Concluding remarks**

The present study reveals that determining deformations with modelled TLS point clouds can be carried out with an accuracy of 1 mm. However, at some monitoring points much larger (up to 3.4 mm) discrepancies between the TLS and the other measuring techniques were detected. Such discrepancies are not only dependent on the applied surveying technologies (measurement accuracies of the instruments, TLS data post-processing methods etc.). They also originate from other sources, such as the across-bridge torsion of the bridge deck due to the asymmetric placement of the static load and the eccentric placement of the survey marks with respect to the TLS monitored surfaces.

A better agreement between the different measuring techniques could have been obtained if the measurement conditions (locations of the corresponding survey marks and instruments) and the loading of the structure would have been common for all of the used measurement techniques. However, in practical cases (as it was demonstrated for the Loobu and Tartu bridges) it is often not possible and feasible. This hampers assessing the suitability of TLS for works demanding sub-millimetre

16 Comparison of TLS and reflectorless tacheometry results for the Southern beam of the Loobu bridge. See the legend for the load scenarios. L.1 to L.9 denote the longitudinal position of the tacheometry marks on the Southern cantilever beam

17 Vertical deformations of the Loobu bridge in epoch III (total load of 200 t after 60 min). The TLS-determined deformations are scale-coloured, whereas the results of the other surveying techniques are depicted proportionally to the length of the scale-coloured arrows. The locations of the levelling and tacheometric marks (SP.1/SL.1 to SP.13/SL.13 and P.1/L.1 to P.9/L.9, respectively) are at the base of the deformation vectors. Note that the blue- and red-toned deformations indicate the downward and upward movement of the bridge, respectively. The contours of the bridge deck/beams/piers/abutments are denoted in black. The grey rectangle marks the location of the load (a pile of cast iron blocks). Values on the horizontal and vertical axes denote the longitudinal and transverse coordinates of the bridge, respectively; units are in metres
Thus, we cannot yet fully confirm its appropriateness. Yet, the results achieved in the study were actually very promising. The use of newer (and technically more advanced) scanners may yield an even better accuracy for deformation studies.

TLS results should be verified by other methods when a sub-millimetre accuracy is required. But TLS proved to be accurate enough to be used as an additional survey method for load tests. When dealing with larger deformations (over 1 cm, quite commonly occurring during a static loading of a bridge), the accuracy of conventional surveying techniques (say, a tenth of a millimetre) may be superfluous. In such cases, deformations could be determined with a high degree of reliability based solely on TLS measurements. TLS provides a complete overview of the 3D spatial distribution of the bridge structure deformations, a feature that may be far more significant to the bridge engineers than achieving the maximum accuracy at a small number of pre-selected locations.

Since TLS (like close-range photogrammetry) covers the entire object of interest with continuous high-resolution data, it is also capable of detecting unexpected deformations in areas where the sparse point-wise techniques, such as precise levelling, tacheometry and dial gauges, miss them. As a remote sensing technology TLS could also be utilised in the final epochs of destructive load tests, thereby ensuring the safety of the surveyors in such hazardous operations.

Further improvement of the TLS performance is related to the data post-processing algorithms. One particular component is the elimination of the TLS measurement noise (most notably on the edges of the object) that does not reflect the actual shape nor the deformation of the structure. Improved algorithms that could make a crucial difference to the quality of the results are still in the development phase. Consequently, the presently required (manual) noise removal and meshing may slightly increase the data processing time compared to the conventional survey techniques.
Acknowledgements

The TLS Leica ScanStation C10, the total stations Trimble S6 and Trimble M3 and the accompanying licensed software used in this study were purchased within the framework of the Estonian Research Infrastructures Roadmap object Estonian Environmental Observatory (project No. AR12019) and maintained within the IUTT2 project. The study was supported by the Estonian Environmental Technology R&D Program KESTA, research project ERMAS, AR12052. The invaluable comments of the three anonymous reviewers are appreciated and lead to significant improvements of the manuscript.

ORCID

S. Märdla http://orcid.org/0000-0003-4140-9374
S. Idnurm http://orcid.org/0000-0003-2998-4499

References


Idnurm, S. 2013. The test programme of Tartu Circuit Railway overpass (Tartu-Beolo Railway at km 3.591) (in Estonian). Dept. of Road Engineering, Tallinn University of Technology.


%20C10/brochures-datasheet/Leica_ScanStation_C10_DS_en.pdf [Accessed 14 July 2016].


Tsikiri.pdf [Accessed 22 October 2014].


Survey Review 2017 15