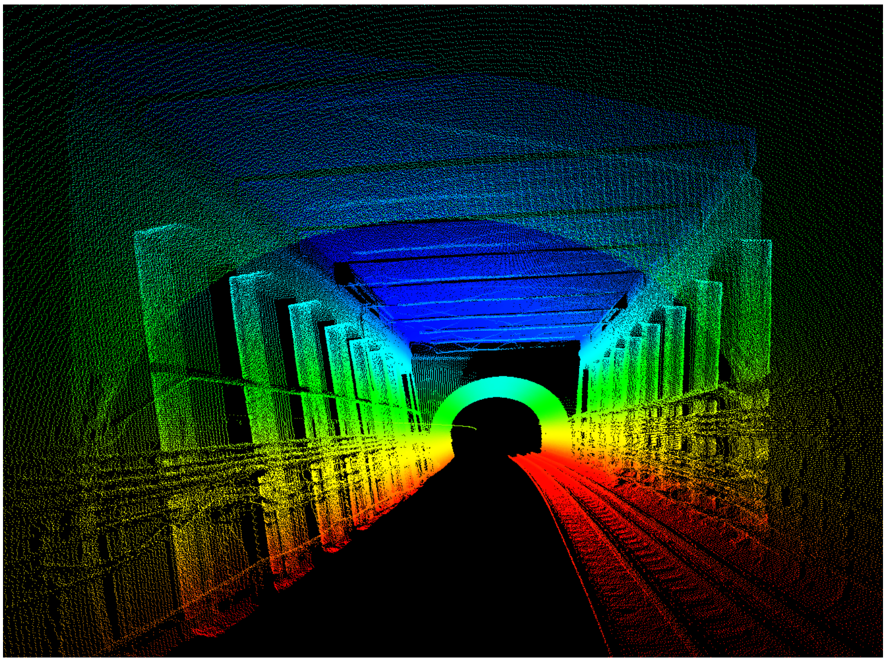
TUNNELINGS SYSTEM



Inspection of brick tunnels and covered ways

SSL (Circle, Hammersmith & City and District Lines)

LONDON UNDERGROUND LIMITED

Inspection date: July 6th 2014

Report date: September 22nd 2014

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1 INTRODUCTION

This document presents the results of the assessment of brick tunnels and covered ways on the SSL, which cover the Circle, Hammersmith & City and District Lines. Brick tunnels on London Underground were constructed in the 1860's and are formed by a process of *'Cut and Cover'*.

The inspection was performed by *Euroconsult* with the *Tunnelings System* at the request of *London Underground Limited*.

The document is organized as follows: First, the performed survey as well as the system are briefly described. Next, Section 4 provides details about the tunnel assessment that has been carried out.

The annexes include a further description of the *Tunnelings System*, and the user guide for the viewer and result analysis software applications. Last, for each one tunnels, score table, statistical analyses and defect mappings are presented.

2 DESCRIPTION OF THE SURVEY

The survey was carried out during the engineering hours of two weekend periods:

- Saturday 28th and Sunday 29th of June
- Saturday 5th and Sunday 6th of July

The inspections was carried out using a locomotive and flat wagon. The metal frame were assembly on the flat wagon and six laser-cameras units were installed to survey half of the section for each run.

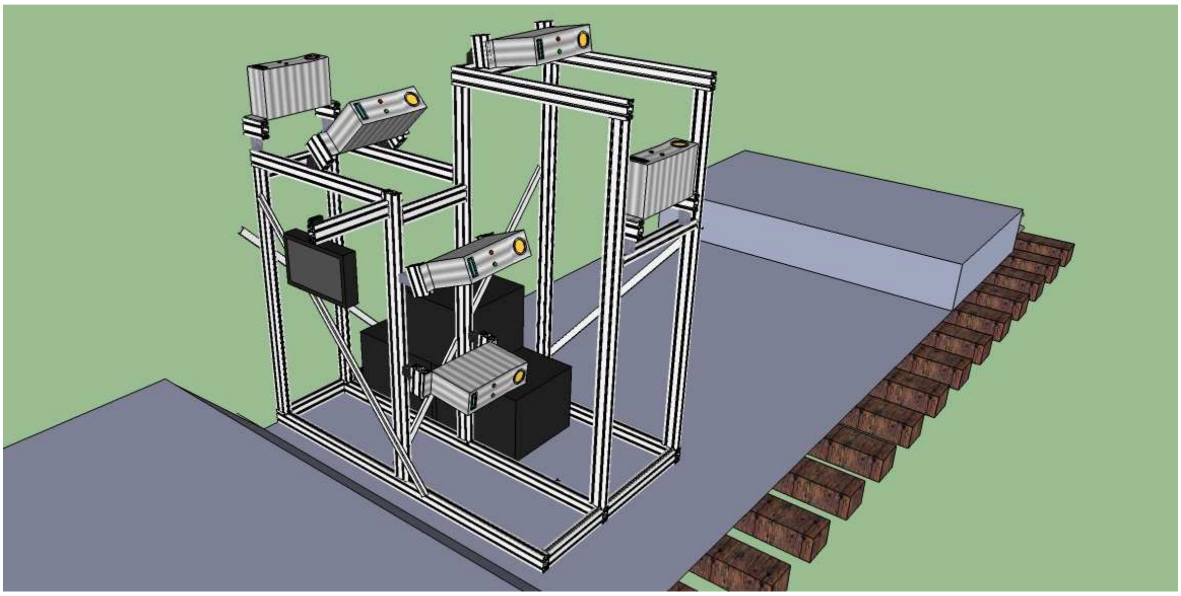


Figure 1. Metal frame with six sensors on flat wagon. Assembly drawing

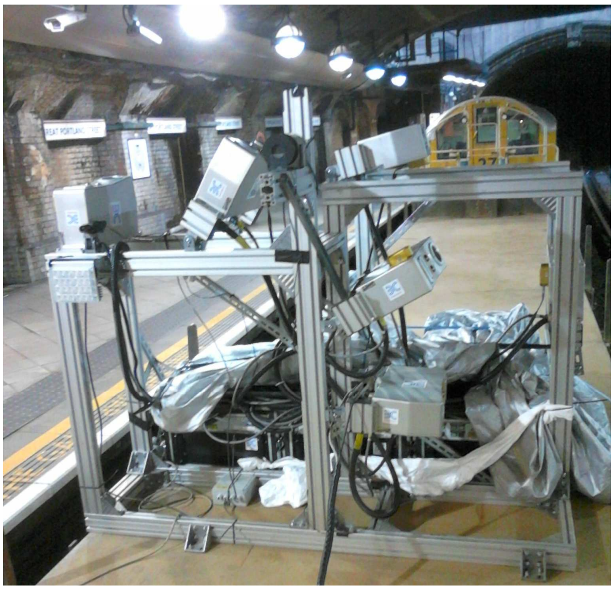


Figure 2. Metal frame with six sensors on flat wagon. Assembly photograph

The inspected sections are those within SSL lines (Circle, Hammersmith & City and District Lines). A map of the section surveyed is depicted in Figure 3.

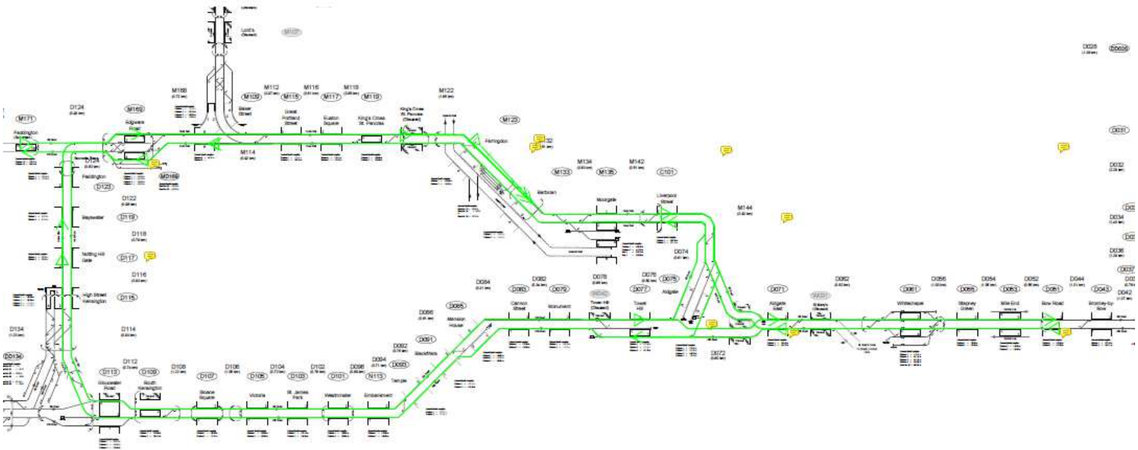


Figure 3. Map of the section surveyed

Two types of tunnels sections had been inspected: brick tunnels, known as TL sections, and Covered Ways. The inspection comprises 34 tunnels ensembles between contiguous stations, 27 of them within Circle line and 7 of them within Hammersmith & City line. As agreed with the Client, the results of the inspection will be provided in two stages so that inspectors can familiarize with the data.

Circle line

SSL1. Aldgate - Tower hill (TL35, CW28, CW38)
SSL2. Tower hill – Monument (CW37/ TL33, CW36, TL32)
SSL3. Monument - Canon Street (TL31)
SSL4. Canon Street - Mansion House (CW27, TL30, CW26, TL29, CW25, TL28)
SSL5. Mansion House – Blackfriars (TL26, CW24)
SSL6. Blackfriars – Temple (TL24, CW23, TL23, CW22, TL22, CW21)
SSL7. Temple – Embankment (CW20, CW19)
SSL8. Embankment – Westminster (CW18, CW17, TL21)
SSL9. Westminster - St James's Park (TL20, CW16)
SSL10. St James's Park – Victoria (CW15, TL19, CW14, TL18, TL17)
SSL11. Victoria - Sloan Square (TL16, TL15, TL14, TL13, TL12)
SSL12. Sloan Square - South Kensington (TL11, CW13, TL10, TL9, TL8)
SSL13. South Kensington - Gloucestrer Road (TL7/TL75)
SSL14. Gloucestrer Road- HS Kensington (TL6/TL74, TL73, CW58)
SSL15. HS Kensington- Notting hill (CW57, TL72, CW56, TL71, TL70)
SSL16. Notting hill – Bayswater (TL69, TL68, TL67, TL66)
SSL17. Bayswater – Paddington (CW55, TL65, CW54, TL64, CW53, TL63, TL62, TL61. CW52, TL60)
SSL18. Paddington - Edward Road (TL59, TL58, TL57, TL55, TL54)
SSL19. Edward Road - Baker Street (TL53)
SSL20. Baker Street - Great Portland Street (TL51, TL110, TL109)
SSL21. Great Portland Street - Euston Square (TL106)
SSL22. Euston Square - King Cross (TL103, CW71, TL102, CW70, CW69, TL101)
SSL23. King Cross - Farringdon (CW67, CW66, TL97, TL91, TL89)
SSL24. Farringdon – Barbican (TL85)
SSL25. Barbican – Moorgate (TL82, CW75)
SSL26. Moorgate - Liverpool Street (CW62, TL79)
SSL27. Liverpool Street – Aldgate (TL77, CW61, CW60)

Hammersmith & City

SSL28. Aldgate - Aldgate East – (TL76, CW59)
SSL29. Aldgate East - White Chappel (TL37, TL38, CW30, CW32)
SSL30. White Chappel - Stepney Green - (CW33, TL41)
SSL31. Stepney Green - Mile end (TL42, TL43)
SSL32. Mile end - Bow Road - (TL44, CW35)
SSL33. Paddington - Edward Road (TL56)
SSL34. Tower hill - Aldgate East (CW29)

*Partially inspected. One half of a different tunnel surveyed in each way.

- Station (not inspected): TL27 (SSL4); TL52, CW51 (SSL19); TL108 (SSL20); TL107, CW73, TL105, TL104, CW72 (SSL21); CW68 (SSL22); TL100 (SSL23); TL87, TL86 (SSL24);
- Dual tunnel (not inspected one): TL83, CW74 (SSL25); TL36 (SSL34).
- Out of surveyed route: TL99, TL78, TL80, CW40, TL125, TL39, CW31, TL5, TL4, TL3, TL2, TL1, TL250, TL145.

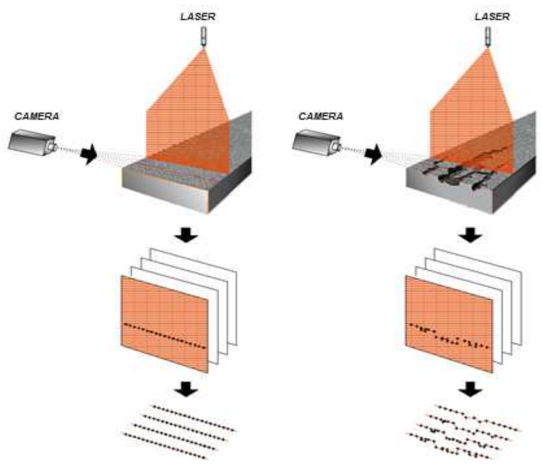
3 BRIEF SYSTEM DESCRIPTION

Tunnelings system is a high-performance inspection system that enables to carry out tunnel evaluations, analysing wall linings and railways with a 1mm resolution at survey speeds up to 30km/h.

Tunnelings is based on the use of high-speed cameras, custom optics and laser line projectors to acquire both 2D images and high-resolution 3D profiles of the surveyed tunnel. It can be operated under all types of lighting conditions, providing high-quality data in both illuminated and shaded areas. The system enables to acquire 3D point clouds as well as 2D images data with 1mm resolution over 12m long arc tunnel sections at survey speeds up to 30km/h. This rapid tunnel condition assessment capability makes it possible to perform long tunnel inspections more frequently on a regular basis and carry out a comparison of several inspections over the same tunnel.

The acquired high-resolution images lighted up by laser emitters enable the analysis automation for flaws detection so that for example cracks, damages, and dampness can be detected and analysed. In the case of brick tunnels, the position of the bricks or any mortar loss can also be analyzed. The provision of 3D information facilitates the evaluation of damages found in the tunnel's surface (in both longitudinal and transverse ways). It allows cross sectional deformations to be located and assessed, as well as missing bricks or masonry units.

Principles of the inspection system



Tunnelings system extracts 3D information by using the principle of triangulation. A pattern of known lighting, a line in this case, is projected from the laser onto the object to be inspected. The line is recorded by a digital camera positioned at a fixed distance, at an oblique angle relative to the projected light. The intersection between the pattern of emitted light and the field of view of the digital camera defines the range of operation of the 3D sensor. The positions of the lighted points on the surface of the object are displayed in the image obtained by the camera and the distance between these points and the camera can be calculated thanks to trigonometry. This technique enables high-quality digital images and superimposed 3D information to be obtained in a single capture, as it can be seen in the following figure.

The sensors used (Figure 2) are laser cameras composed of a laser line projector and a digital scanning camera, which are monitored by a control unit. Each pair of cameras is controlled by a control electronics device to ensure the synchronized acquisition by a pair of laser cameras. The following are the sensors' main features:

- Depth accuracy: 0,5mm.
- Sampling rate: at least 2,800 profiles/second
- Longitudinal resolution (profile spacing): usually 1mm (adjustable)
- Transverse resolution: 2,048 points/profile. The suggested trade-off between transverse accuracy and transverse field of view is 1mm – 2m.

Figure 4. Cameras and control electronics devices.

The structure that carries the laser cameras used for the inspection can be fitted on a truck or wagon bed. A mechanical system is employed to position its arms so that the system constantly matches the geometry of the tunnel, as the following Figures show.

Figure 5. Examples of structures used for the tunnel inspection task.

With the most comprehensive configuration the vehicle can normally hold up to six laser cameras. Each laser camera unit carries out the inspection by using the most common setting – a 2m wide section with an accuracy of 1mm.

Figure 6. Mechanical installation of an inspection arm holding six sensors.

A high-resolution odometer (20,000 pulses per revolution) is also installed, as well as a monitoring and control system, composed of an industrial computer for the sensors' synchronization and a monitor for control and monitoring tasks. The acquisition spacing can be set by the system operator to obtain the most convenient trade-off between speed and resolution. The signal received from the odometer is used to trigger all the sensors at the exact same instance.

The data provided by *Tunnelings* comprises 3D images that contain information in a radial way relative to the direction of the condition survey, and 2D images with grayscale intensity information. The following figure shows a 2D image, a profile and a 3D image. The white pixels shown in the depth image indicate there is more depth.

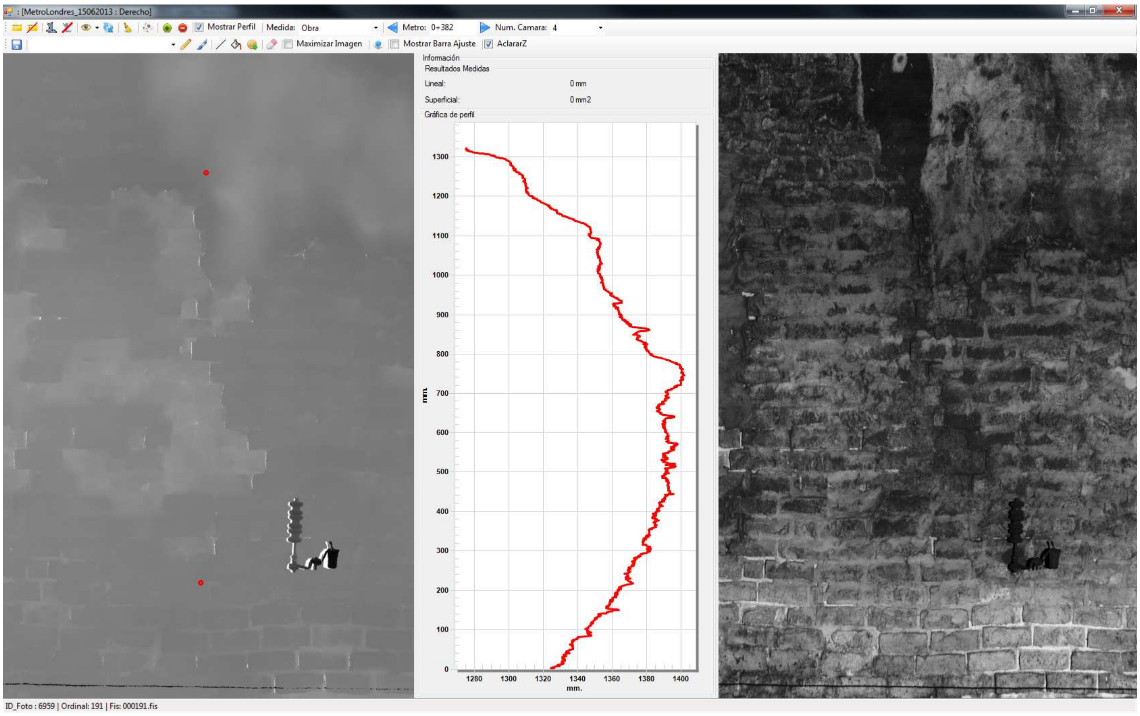


Figure 7. Transverse sections of the bricks' lining obtained from the available 3D data information. The middle one is the profile, right one is 2D and left one is 3D.

High-quality digital images and a 3D reconstruction of the inspected area can be obtained from the captured data, as the following figure shows.

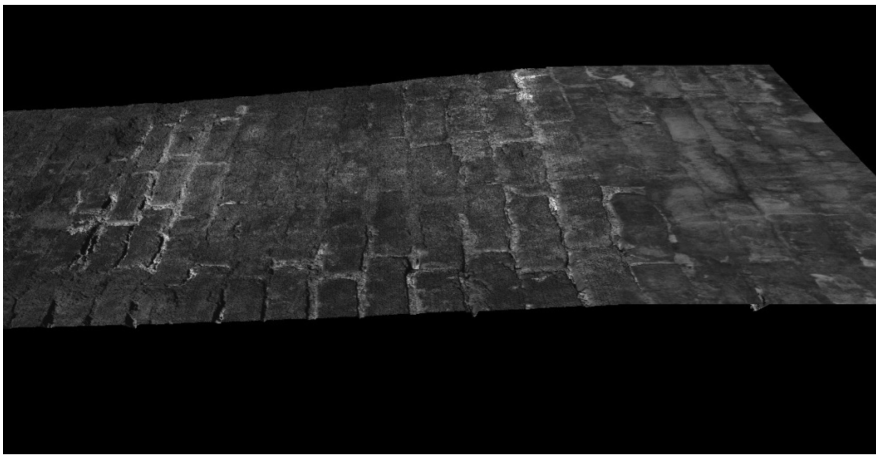


Figure 8. 3D reconstruction.

The software enables to arrange the images in a wider view of the lining and then proceed with its measuring or represent and superimpose the analyzed defects.

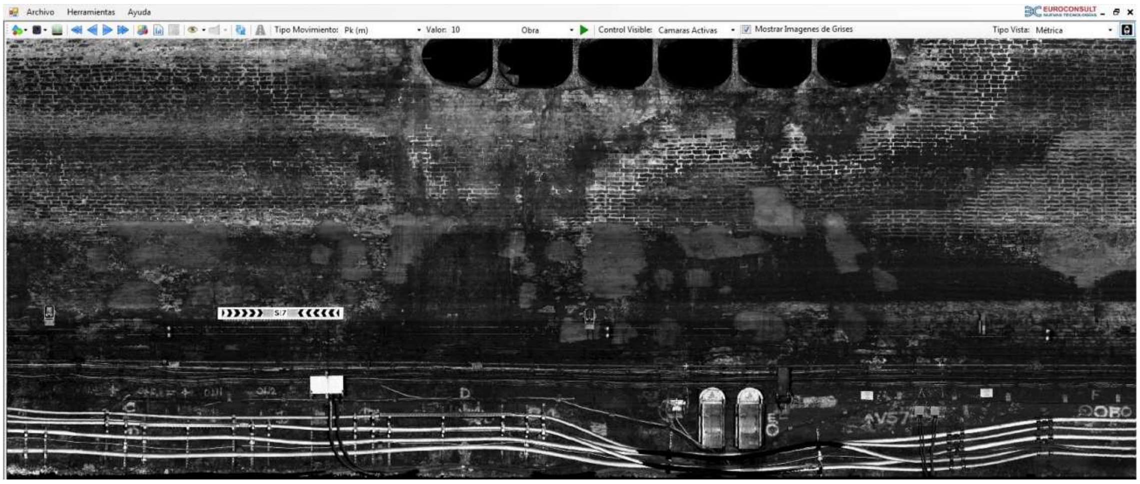


Figure 9. Half section view.

The software application comprises tools and utilities to combine the images along both longitudinal and transverse directions, and display in a superimposed way tunnel sections together with the different defects or information of interest regarding the analyzed section.

All the analysis data are stored in databases which can be quickly referred to by means of relative coordinates, milestones or user-defined reference points. The application also provides tools for the manual marking of defects as well as expert annotations. It also enables the engineer in charge of the inspection to automatically check or verify the previously analyzed defects.

4 CONDITION SURVEY

The aim of the survey campaigns was to have a high-resolution three-dimensional visual record of the tunnel's lining, which was acquired at a high-performance rate. The interest in this inspection consists in detecting any possible pathology that might affect the tunnel exploitation and its evolution over time. Therefore, following the above described goal, the incidences that have been analysed on the lining have been grouped into the following different categories:

1. Mortar loss in joints
2. Lining face loss
3. Cracking
4. Damp patches

A summary of overall ratings about the tunnel condition is presented in Section 4.1. Some examples of each one of the defects detected in a brick tunnel are depicted in Section 4.2. A comprehensive analysis is provided thanks to the software application.
The assessment of the different defects that have been found for each one of the inspected tunnels are presented in **Annex 3**: first a score table, then statistics obtained by means of the aforementioned software, and finally a mapping of the tunnel defects.

The statistical analysis is based on the data provided by the previous image analysis, and is performed by means of a numerical processing and a graphic representation of the incidents. The statistical revision of all the data throughout the tunnel enables to extract those areas where the presence of mortar loss in joints, cracking, lacking of material and dampness is more relevant. The most representative graphs of the surveyed tunnel lining condition can be found below. However, the software makes it possible to acquire a greater level of detail with respect to the analysis, and to carry out multiple combinations and queries about pathologies and surveyed sections as well. The results are presented by adding them on each three meter of the tunnel, that is, they show the length or incident area gathered in a section of a 3 meter width.

4.2 EXAMPLES OF RESULTS

The following examples represent the evaluated defects and the type of analysis that can be performed.

4.2.1 Cracking

This category deals with cracking, showing an obvious opening between its edges. It has been both in the intensity and depth images (3D).

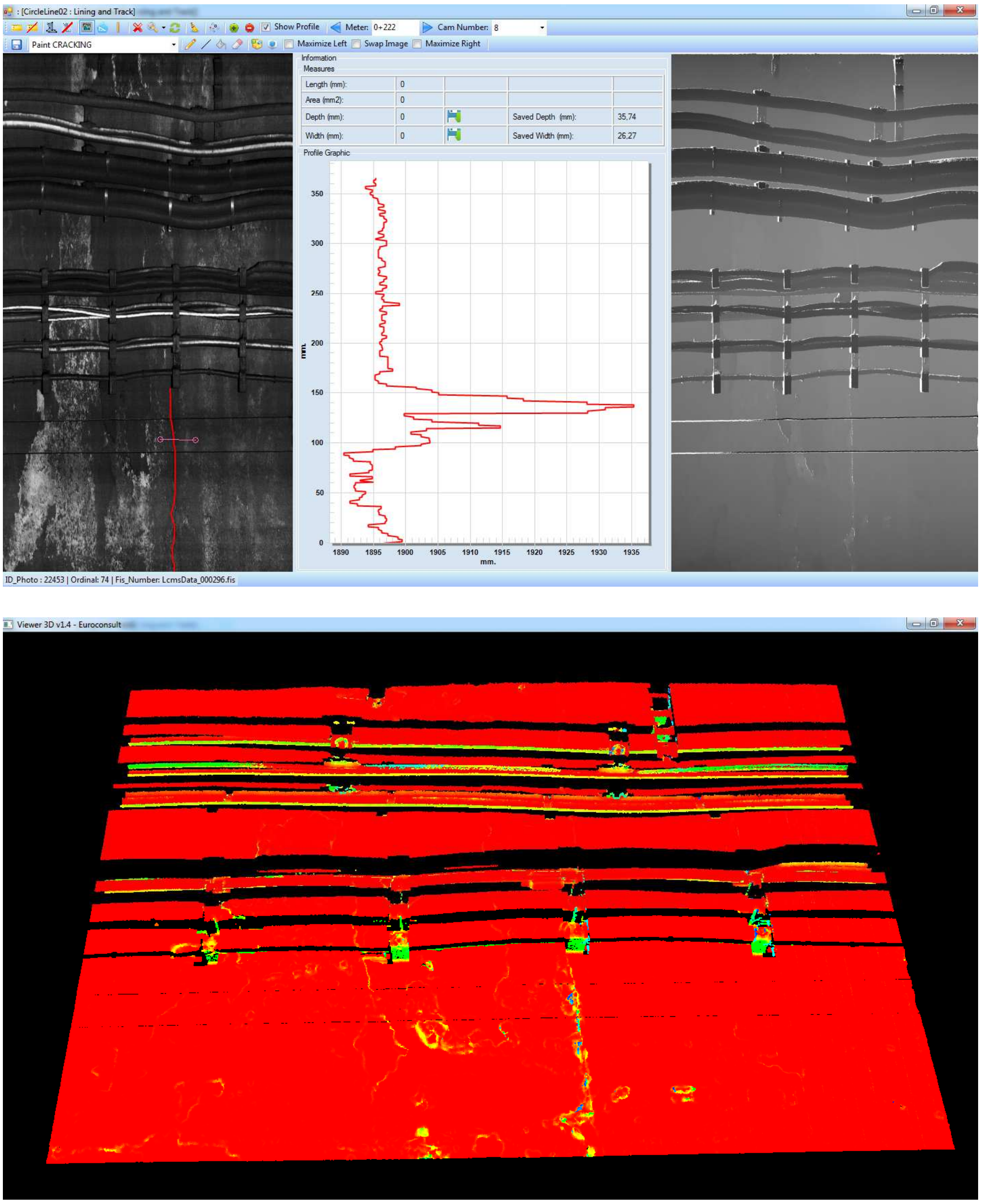
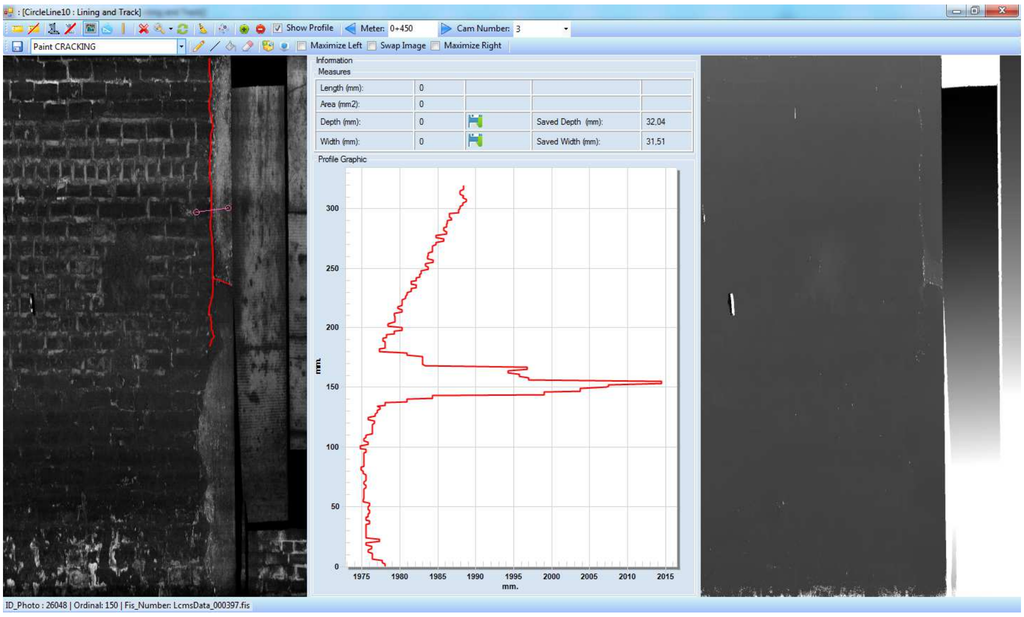


Figure 11. Cracking example. Tower Hill – Monumet (TL32)



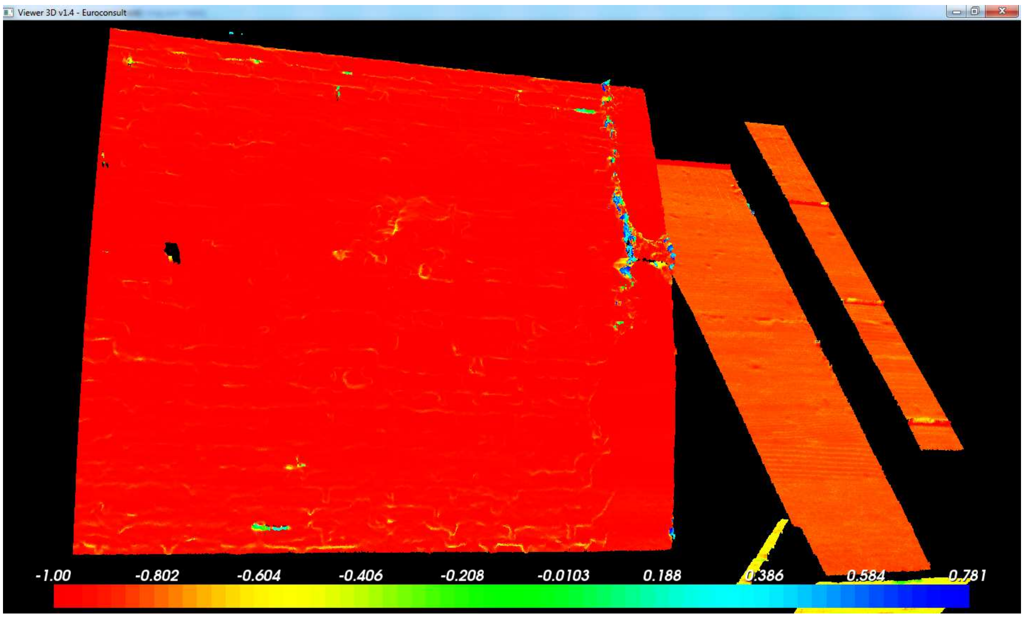
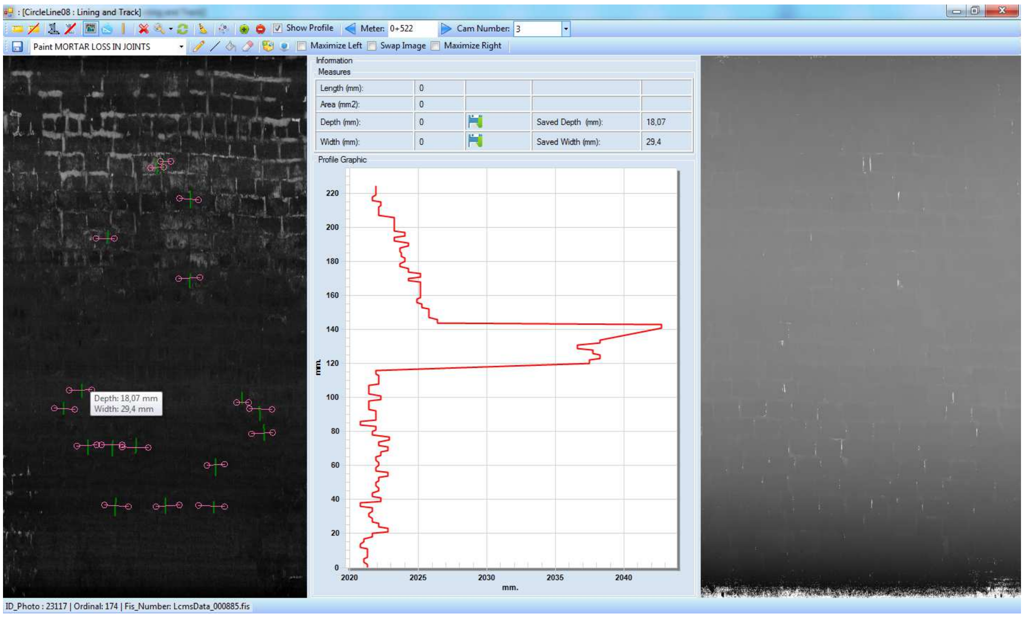


Figure 12. Cracking example. St James's Park – Victoria (TL17)

4.2.2 Mortar loss in joints

This category presents the bricks' joints that have been detected on the lining. Thanks to the 3D image, both their width and depth can be clearly assessed. The lack of material in these joints has not been treated yet. In addition to this, they do not reveal any previous presence of water.



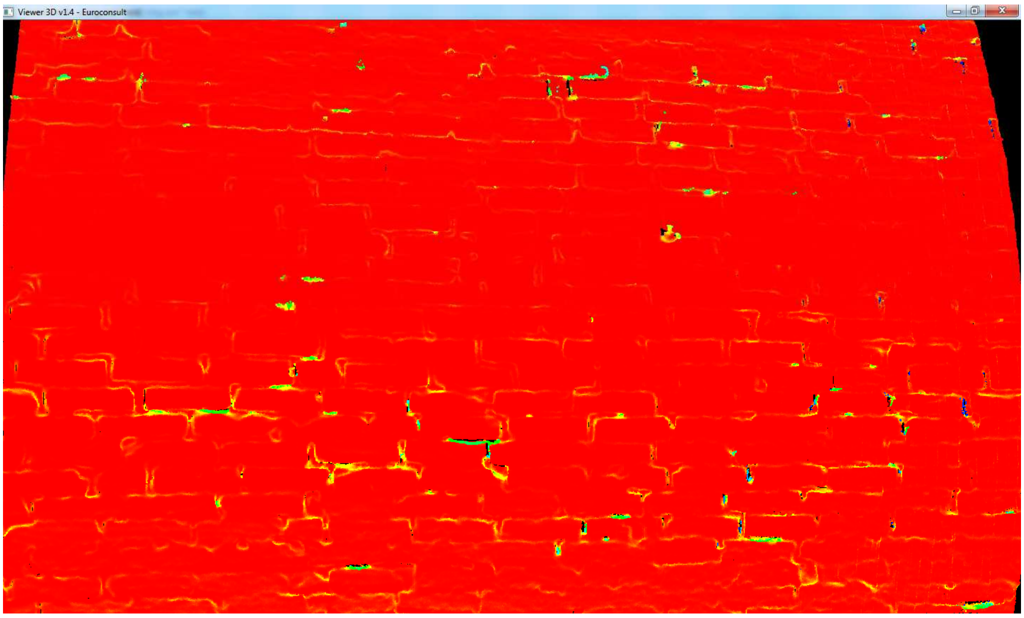


Figure 13. Mortar loss in joints example. Embankment – Westminster (TL21)

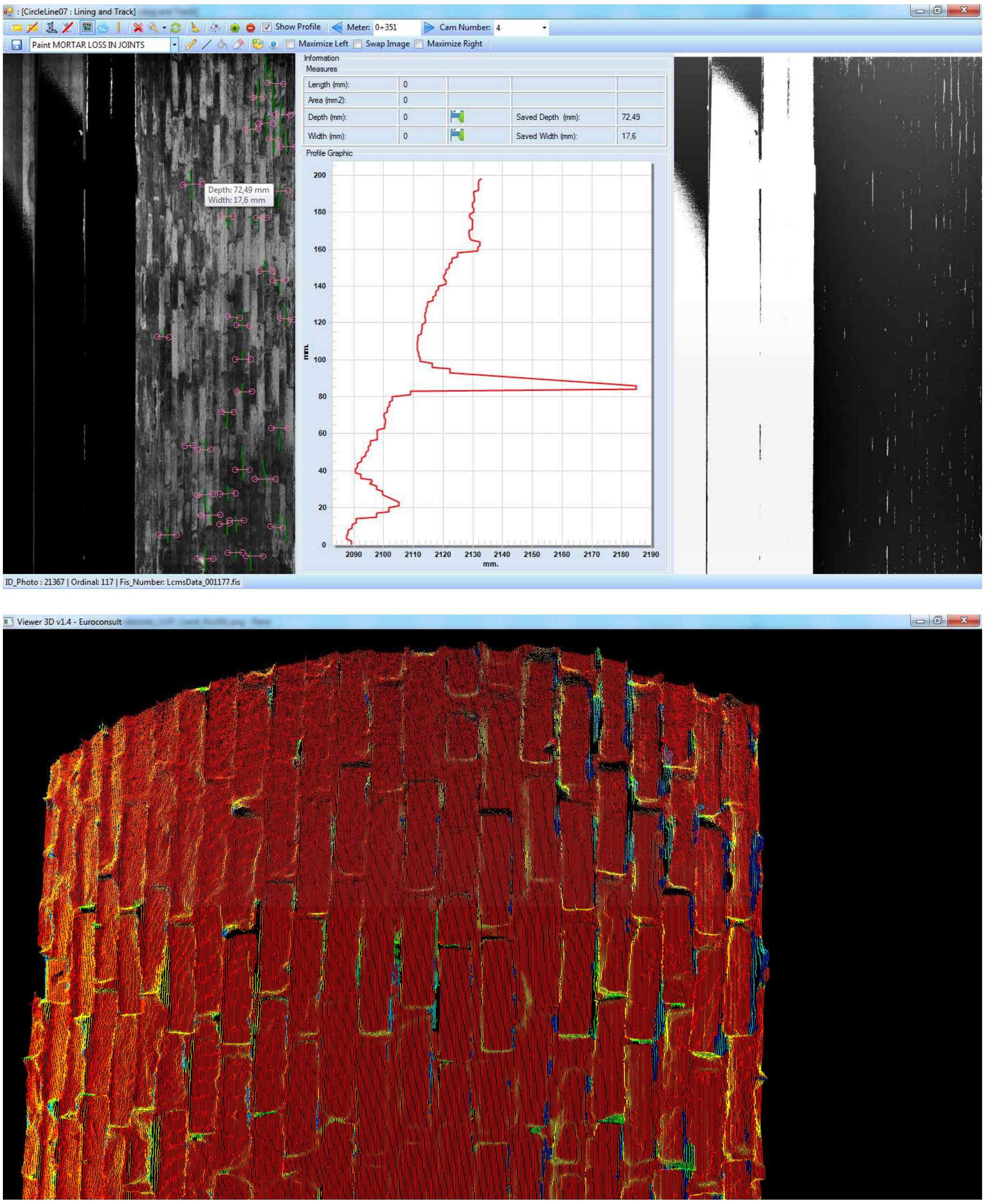


Figure X. Mortar loss in joints example. Temple – Embankment (CW19)

4.2.3 Lining face loss

The areas on the bricks that show significant lining face breaking, missing parts and major material loss have been here stressed. These areas are automatically detected thanks to the 3D image and have been clearly marked on the surface as irregularities distorting the theoretical profile of the tunnel.

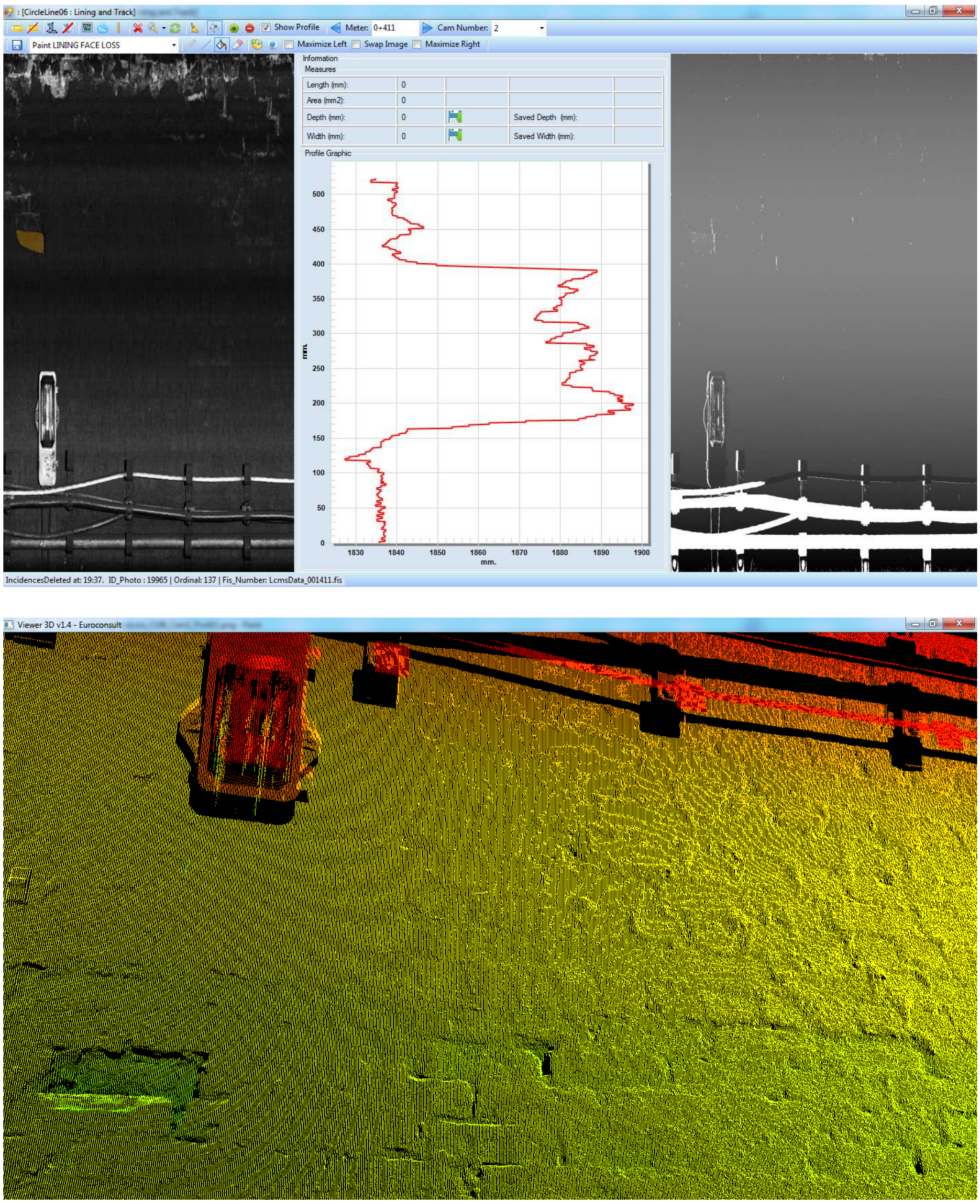
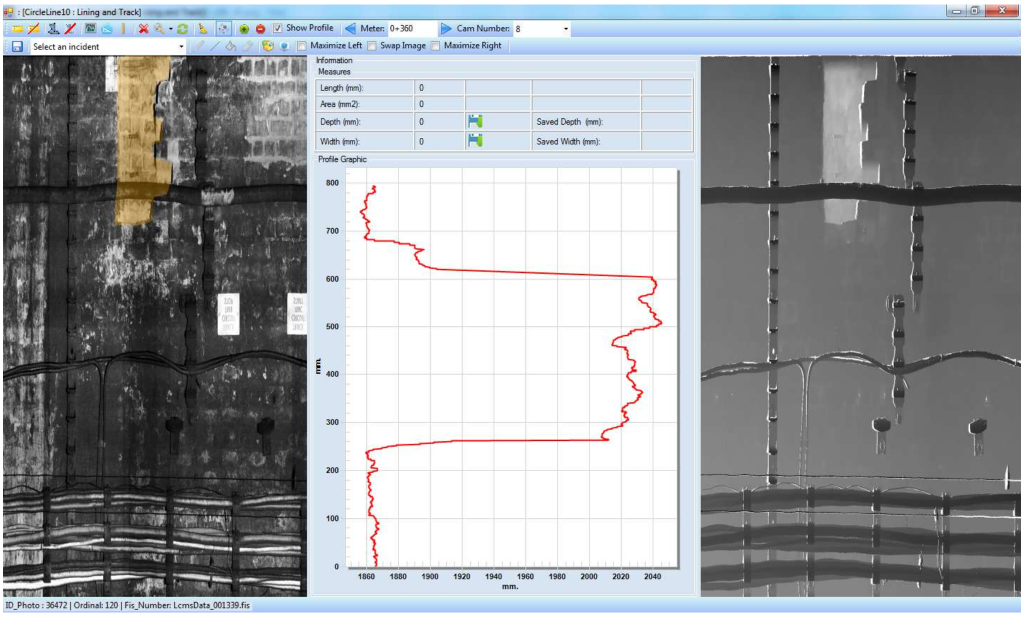


Figure 15. Linning face loss example. Blackfriars – Temple (TL22)



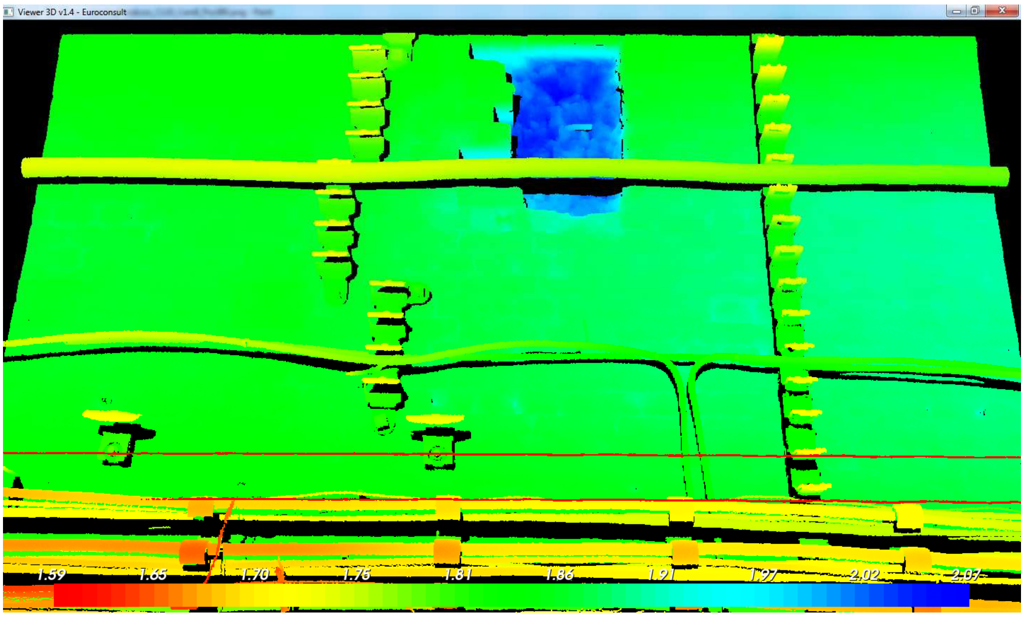


Figure 16. Linning face loss example. St James's Park – Victoria (TL17)

4.2.1 Water ingress and dampness

For the purpose of analysing any dampness in the tunnel, areas in which a surface run-off has been detected and areas which show dampness coating have been detected as damp patches.

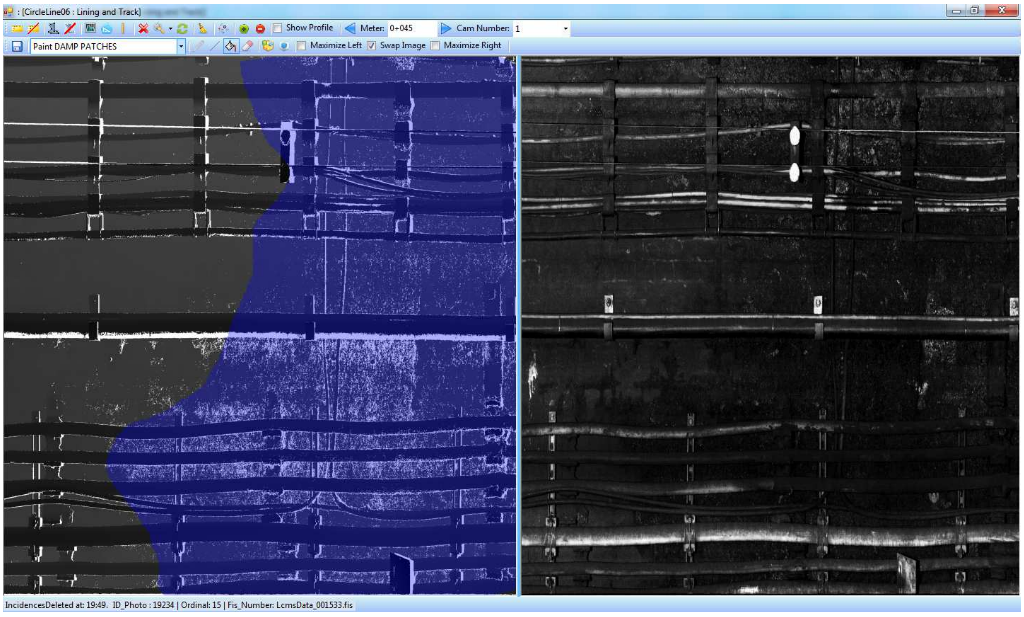


Figure 17. Blackfriars – Temple (TL23)

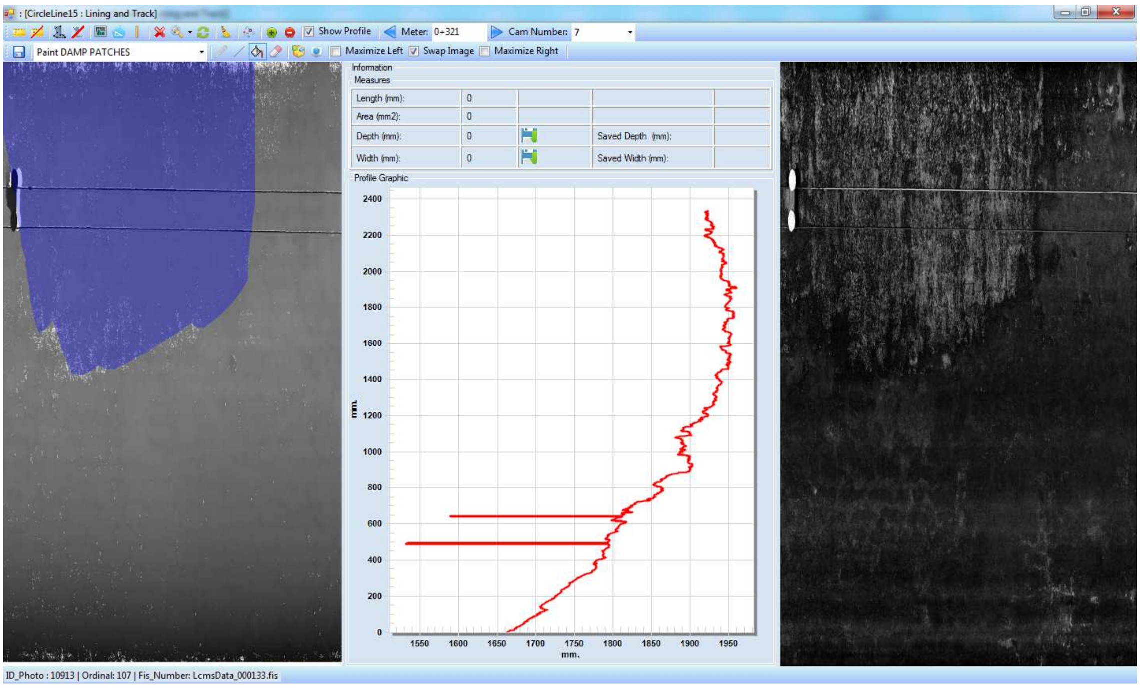


Figure 18. HS Kensington- Notting hill (TL71)