II International Conference on Particle-based Methods – Fundamentals and Applications
PARTICLES 2011
E. Oñate and D.R.J. Owen (Eds)

ADVANCED MONITORING AND NUMERICAL TECHNIQUES FOR ASSESSING THE STABILITY OF TUNNELS

HAN-MEI CHEN[*], PROF HAI-SUI YU[†] AND DR MARTIN SMITH[†]

[*]Nottingham Centre for Geomechanics, Faculty of Engineering,
The University of Nottingham
Email: evxhc@nottingham.ac.uk
[†] Email:hai-sui.yu@nottingham.ac.uk

[†] Institute of Engineering Surveying and Space Geodesy, Faculty of Engineering, The University of Nottingham
Email: martin.smith@nottingham.ac.uk

Key words: Advanced Monitoring techniques, Tunnel Stability.

Abstract. *This research aims to develop an advanced monitoring technique for assessing the stability of tunnels, which may substitute or supplement the conventionally manual procedures.*

In this paper, 'laser scanning technique' is primarily studied to determine the utilisation of laser scanners for condition monitoring of lined tunnels. A series of model tests have been *carried out by using laser scanning technology, in which models were set up simulating tunnel conditions. After scanning and processing in the corresponding software, 3D coordinates of the models were obtained as well as 3D 'point clouds' models. Thus various defect targets like cracks and deformation on the tunnel wall could be identified and measured efficiently in these digital models. Precision and limitations related to laser scanning were also highlighted. In addition, numerical simulation would also be conducted using $FLAC^{2D}$ and $FLAC^{3D}$ software to link the simulated tunnel behaviours to overall structural stability.*

This study indicates that laser scanning technique has potential for executing condition monitoring, such as depth and width of cracks, deformation of tunnels, with high accuracy in a static mode of scanning. By these observed information combined with numerical analysis, the stability of the tunnels could be assessed for safety.

1 INTRODUCTION

Most tunnels in UK are built decades ago, some are even over a hundred years old. Degradation and tunnel deformation are major threats to tunnel's stability which lead to a collapse of a tunnel if not controlled. Therefore monitoring and examination of tunnels are important to diagnose the deterioration and conduct repair work, before serious damage occurs.

Tunnel inspection has predominantly been a manual procedure, which is time-consuming and subjective, giving rise to variance in standards and quality of examinations for tunnels. The overall aim of the study is to develop an automated technique which may substitute or augment the manual tunnel examination survey in the demand for higher efficiency as well as standardisation of tunnel inspections. Initially, a series of laboratory tests are conducted to study the utilisation of laser scanning system for condition monitoring of lined tunnels.

Furthermore, numerical models are needed to be developed according to the current monitoring results, to predict and assess the future status of the tunnel.

2 LABORATORY WORK WITH THE TERRESTRIAL LASER SCANNING (TLS) SYSTEM

2.1 Brief introduction to the TLS system

The TLS technique has been recognised as a promising tool in the field of engineering over the past few years as it quickly provides a realistic representation of objects [1]. Moreover, the TLS system provides dense point clouds of the scanned surface coordinates to build a 3D model of the target. As several papers revealed the potential of laser scanning in accurately mapping surface displacements in underground excavations [1] and detecting damage parts on tunnel walls [5], it would be very interesting to utilise the TLS for condition monitoring in tunnels, such as crack depth and the deformation of tunnels.

There are two laser scanners employed in the experimental work, namely a RIEGL LMS-Z420i laser scanner and an improved laser scanner, the RIGEL VZ-400. It is expected that the scanning results for the later would be collected faster and have a better performance in respect of accuracy.

2.2 Designed test models

Intact model 1: The bricks used in the first model are brand-new red, smooth Norman bricks. Each brick is 215×105×73mm (L×W×H). The bond pattern is 'Stretcher bond' inserting a half-brick setting every second row. Figure 1 shows that the whole model has been divided into 9 test areas each with different brickwork properties.

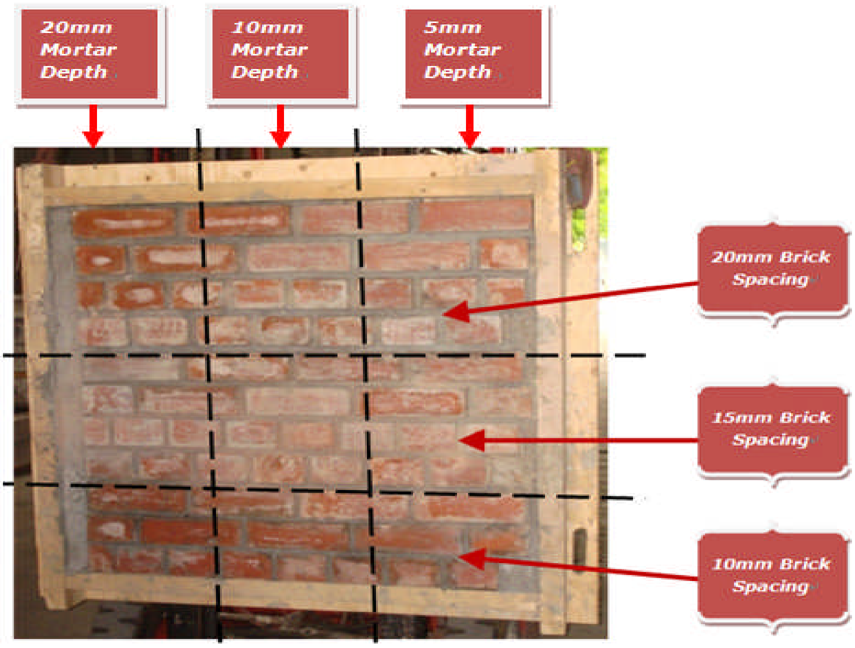

Figure 1: The division of model 1

The aim of setting up this model was to establish what the scanner could detect in undamaged brickwork and to form a base model reference for different systems.

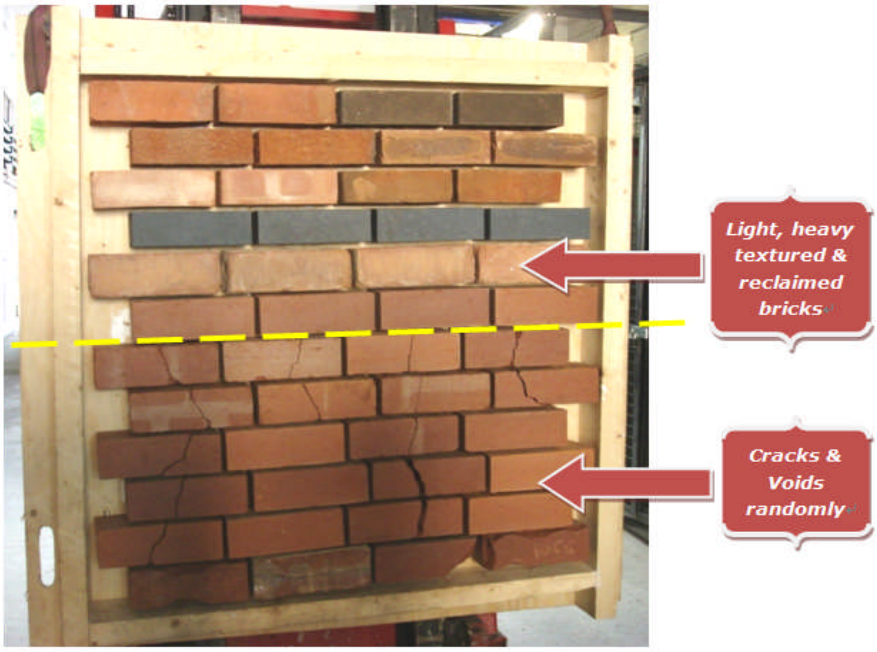

Figure 2: The division of model 2 (Surface texture & cracks)

Model 2 (with cracks & surface texture): The second model (Figure 2) has been separated into 2 parts. The bricks of upper part are a mixture of smooth, pattern textured, and reclaimed bricks. The reclaimed bricks simulate weathered bricks in railway tunnels to see how brick texture could influence the scanner. The lower part of the model uses smooth bricks as in model 1. It contains roughly 11 narrow artificial cracks throughout the area, each of which is approximately 3mm wide.

It also contains a big crack 12mm wide and a small void. The brick spacing in model 2 is 10mm. The entire model was built without mortar to simulate heavily recessed weathered mortar in real railway tunnels and to establish how far the scanner could see into the open joints.

The objective of setting up this model was to discover the influence of the texture of the brick surface as well as to determine the visibility of the laser scanner on deep narrow cracks and deep mortar depth.

2.3 Laboratory and measuring work

The experimental work was carried out by both laser scanners separately at the measuring distance from 2m, 4m to 6m (Figure 3). After that, all the measurements were conducted manually in the software by taking an average, such as measuring mortar depth, crack width and brick spacing width.

Figure 3: The scanning process of model sample 1 at the measuring distance of approximately 2m using the RIEGL LMS-Z420i

2.4 Post-processing results and discussions

After initial data processing and measuring work with the RiSCAN PRO software, the results to be discussed are listed:

1) Comparison of images for different angular resolutions using the LiDAR RIGEL VZ-400
2) Comparison of the LiDAR RIGEL VZ-400 & LMS-Z420i on results for
   - Accuracy of mortar depth
   - Noise from the brick surface (after triangulation)
   - Possibility of measuring width of brick spacing and cracks

The factors influencing the accuracy of laser measurement such as weathered mortar depth are concluded here:

- *Physical accuracy and beam divergences of different laser scanner*
- *Hand-made measuring accuracy on the software*
- *Inclined scan direction effect* : (Illustrated in Figure 4**)**
- *Skew scan direction effect* : (Illustrated in Figure 5**)**
- *Different measuring distances*: For instance, with the RIGEL VZ-400, an angular resolution of 0.041° could achieve a discrepancy of 2% for the average measurement of mortar depth up to a distance of 6m. While at the distance of 2m, the discrepancy is around 9%.
- *Different angular resolutions*: In theory, the smaller the angular resolution is, the better the accuracy is. Whereas it is not practical to use the very small resolution with much

more scan time. Therefore various angular resolutions are set up to find an appropriate one with high accuracy.

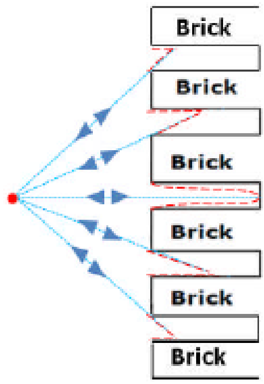

Figure 4: The potential indentation between bricks by laser beam

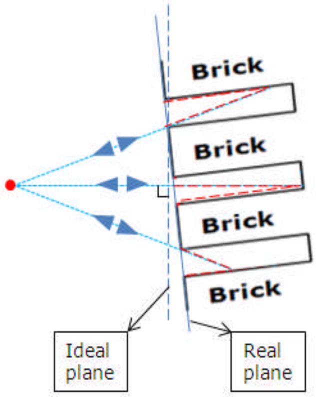

Figure 5: The plan view of scanning process

3 NUMERICAL MODELLING OF ROCK TUNNELS

3.1 Modelling of an unlined rock tunnel

Model assumptions: The total model size chosen for a series of model tests is 207m wide by 87m deep (See Figure 6). For model simplification, only half of the model (103.5m wide by 87m deep) is simulated in FLAC^{2D} considering the model section symmetry. A horseshoe tunnel is 30m below the surface, 100m away from either left or right boundary of the model, sized 7m wide, 3.5m for both side walls and radius 3.5m for the arch. Both left and right boundaries are fixed in x-direction, and the bottom boundary is fixed in y-direction.

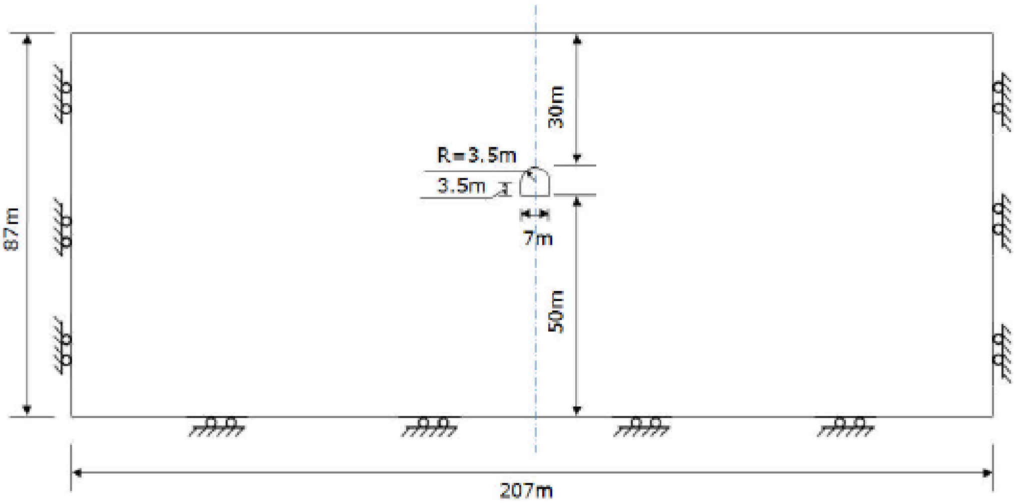

Figure 6: Geometry of the model with boundary conditions

The tunnel is only subjected to the self weight of the surrounding rock which is homogeneous. The density of the rock is 2700 kg/m^3. The top boundary of the model domain represents a free surface.

Different values of rock mechanical parameters as cohesion (C), friction angle (φ), elastic modulus (E) and Poisson’s ratio (ν) were chosen for each modelling test shown in Table 1, to find the influence of rock material on tunnel stabilization.

Table 1: Basic values of mechanical parameters for each test

Friction angle (°)	Poisson's ratio	Elastic modulus (GPa)	Cohesion (MPa)
35	0.3	50	0.8
20	0.2	0.5	0.5/0.2/0.15

Modelling results and discussion

Deformation status: Two hyperbolic curves in Figure 7 similarly demonstrate that relatively lower cohesion of the rock around tunnel (e.g. 60KPa) would induce a larger displacement at tunnel invert. From the cohesion above 500KPa, the invert displacement is stable to 0.173mm. In the two graphs, the elastic modulus changes from 50GPa to 0.5GPa. Accordingly, the displacement of the invert centre point at the same cohesion is increased. The displacement shows a linear relation with elastic modulus.

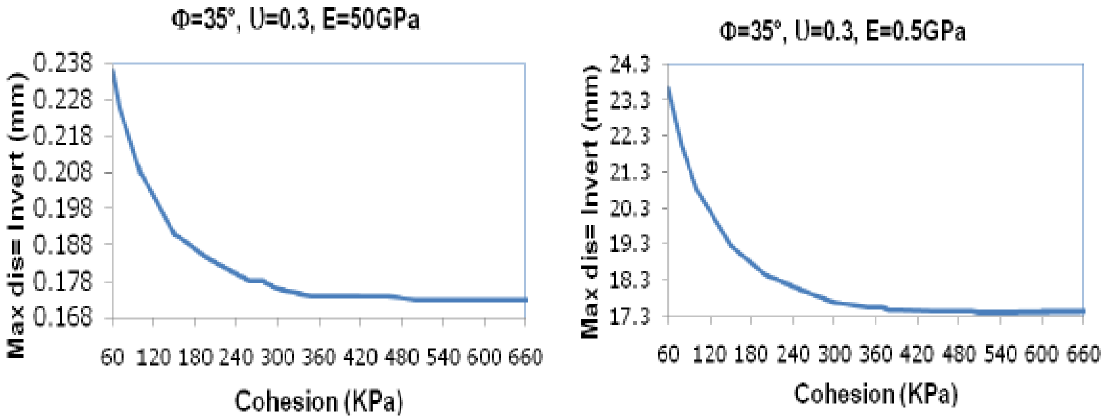

Figure 7: Relation between cohesion of the rock and the displacement of the tunnel invert

Yield status: In general, the yield area enlarges gradually as the cohesion decreases. Cohesion is the most effective parameter corresponding to the tunnel failure compared with other parameters, by studying the contour outputs.

4 CONCLUSIONS AND FUTURE WORK

4.1 Laboratory work

The presented studies showed the great potential of laser scanning in tunnel monitoring work. In future laboratory work, some improvements would be studied using laser scanners, such as to overcome the angle effect and to have a series of moving scanning processes to increase the scanning speed through a tunnel section.

4.2 Data post-processing

The measuring work for brick spacing and mortar depth has done manually using the RiSCAN PRO software which is not accurate enough. Further automated analysis techniques such as Matlab are needed to be developed for better precision.

4.3 Numerical modelling

Both concrete lining and steel arches have been modelled basically to study the mechanical behaviour of the weak rock tunnel. The next step will specially focus on simulating brickwork arches as a form of railway tunnel support, which will be much challenging due to the composite complexity.

Using $FLAC^{2D}$ could not simulate tunnels surrounded by un-uniform geotechnical materials. Therefore, more work need to be done using $FLAC^{3D}$ as a 3D mode.

5 REFERENCES

[1] Lemy, F., S. Yong, and T. Schulz. *Assessment of laser-based displacement mapping in an underground opening*. 2007. Vancouver, BC, Canada: Taylor and Francis/Balkema.

[2] Turner, A., et al. *Evaluation, and management of unstable rock slopes by 3-D laser scanning*. 2006.

[3] Martin, *Comparison of terrestrial-based, high resolution, LiDAR and digital photogrammetry surveys of a rock slope*, in *Rock Mechanics*. 2007, Taylor and Francis/Balkema. p. 37-44.

[4] Sturzenegger, M. and D. Stead, *Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts.* Engineering Geology, 2009. 106(3-4): p. 163-182.

[5] Yoon, J., M. Sagong, and J. Lee, *Development of damage detection method on the tunnel lining from the laser scanning data.* 2007.