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Ground deformation measurement due to model tunnelling with tunnel roof reinforcement using close range photogrammetric technique

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ABSTRACT: The measurement of ground deformation plays a key role in the laboratory experimental model work. In this study, the close range photogrammetric technique was used to measure the ground deformation subjected to the model tunnel excavation and then it compared to FE numerical analysis. Also, comparison between steel pipe reinforced model tunnel and unreinforced model tunnel was carried out. Consequently, the measured data can be converted to displacement vectors and contours through the image processing.

1 INTRODUCTION

In urban areas, underground structures have been increased dramatically due to the large population and lack of surface spaces. For this reason tunnel excavations have become necessary. However, the construction of any tunnel will give rise to ground deformations. In order to investigate ground behaviour subjected to tunnel excavation, the measurement of ground deformation is very important in the laboratory experiment. Close range photogrammetric technique using digital camera has been used for measuring the ground behaviour clearly and quickly. It shows that high reliability and precision can be achieved in terms of displacement data (Lee, 2006). The close range photogrammetry was demonstrated and introduced to measure the ground deformation data caused by excavation of tunnel in the laboratory model tests. This study discusses the comparison of steel pipe reinforced model tunnel and unreinforced model tunnel using the close range photogrammetric technique. In addition, a numerical procedure of tunnel excavation for the finite element analysis will be proposed.

2 TUNNEL EXCAVATION IN LABORATORY MODEL TEST

2.1 *Model tunnel device*

In order to measure the ground deformation for tunnel excavation, the authors developed the model tunnel device. The model tunnel consists of plastic frame, membrane and hydraulic pump (see Figure 1). The outer diameter of the tunnel is initially 100 mm. The tunnel diameter is gradually reduced by an amount of water. The reduction of the tunnel diameter provides a volume loss (V_L). This volume loss per revolution is determined from the calibration result.

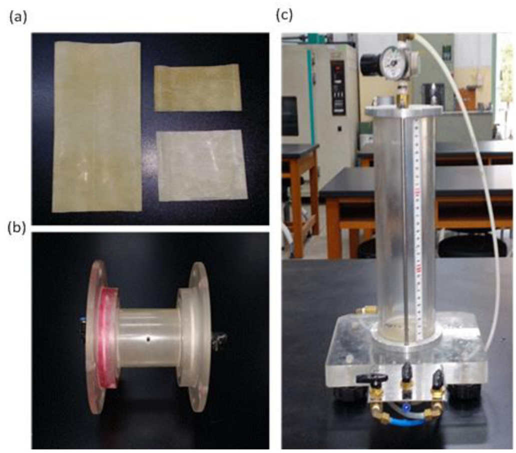

Figure 1. Model tunnel device: (a) membrane, (b) plastic frame, (c) hydraulic pump.

2.2 *Calibration of model tunnel*

To obtain the values of the volume loss (V_L) during the reduction in diameter of the model tunnel, the calibration test was first carried out by measuring the perimeter of the model tunnel. And then value of calibration determined through reduction of the tunnel diameter by controlled an amount of water. The two-dimensional volume loss was determined from the calibration test result, as shown in Figure 2. The calibration test was repeated for 12 times. The result of the calibration test is shown in Table 1 and Figure 3.

2.3 *Model test*

Test apparatus
The soil container box is rigid, a rectangular steel frame (1500 mm in width × 1000 mm in height × 100 mm in

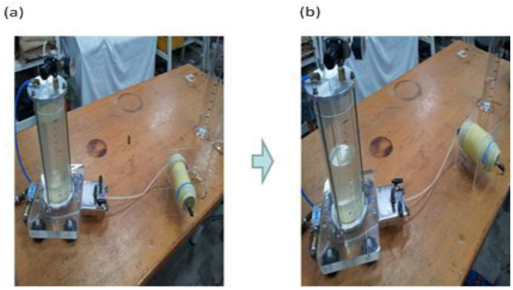

Figure 2. Tunnel calibration test: (a) Maximum shrinkage (V_L of 40 %), (b) Maximum expansion of tunnel diameter.

Table 1. V_L (%) data in tunnel calibration test.

Step	Amount of water (mL)	Diameter (mm)	V_L (%)
0	801.5	9.94	0
1	787.3	9.86	1.5
2	773.1	9.78	3
3	754.2	9.68	5
4	735.4	9.57	7
5	707.0	9.41	10
6	669.2	9.20	14
7	631.5	8.99	18
8	423.8	7.83	40

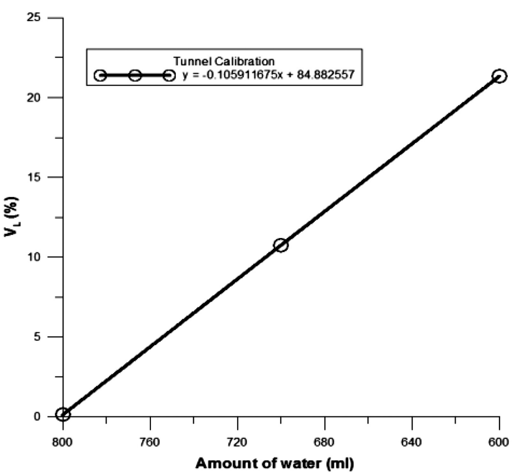

Figure 3. Calibration for the model tunnel device.

length). 18 control points as shown in Figure 4(a) are permanently attached to the steel frame and act as static reference markers and delineate the boundary of plane strain conditions.

Steel pipe reinforcement
Aluminium rods are assumed as steel pipe reinforced ones (6 mm in diameter and 100 mm in length). A total of 13 steel pipe reinforced are used. The weight of aluminum rod is 5.8 g. A distance between the steel pipes is 100 mm.

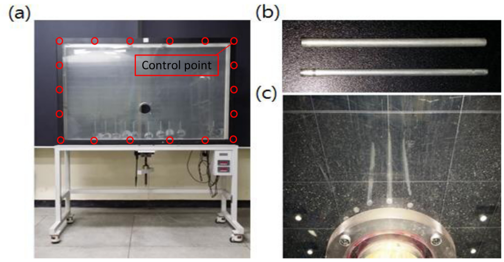

Figure 4. Test apparatus: (a) soil container box, (b) diameter of 5 mm and 6 mm aluminium rods have assumed to target points and steel pipe reinforced, (c) insertion of steel pipe reinforced.

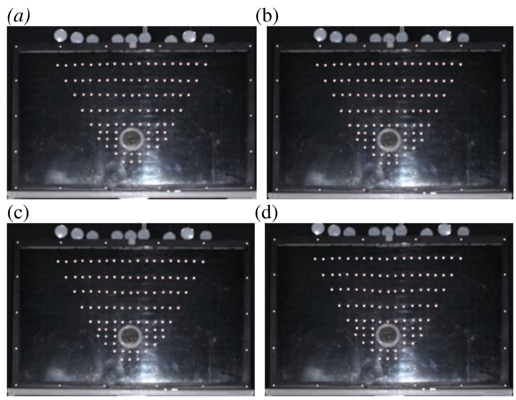

Figure 5. Ground deformation of tunnel excavation (unreinforced model tunnel), (a) $V_L = 5\%$, (b) $V_L = 10\%$, (c) $V_L = 18\%$, (d) $V_L = 40\%$.

Test procedure
In the preliminary test, soil property test and calibration of model tunnel were performed. Next, ground was set up in the model soil container and combine with the model tunnel device. After that, aluminium rods were inserted at the tunnel crown level in the container box. All the tests start through reduction of the model tunnel diameter by controlled an amount of water.

2.4 *Results of model test*

Ground deformation
In order to measure the ground deformation, the authors have conducted close range photogrammetry. Figure 5 shows the results of ground deformation due to the model tunnel excavation with out steel pipe reinforcement.

Settlements of ground surface
As shown in Figure 6, the dial gauges used in model test and the position of dial gauges are arranged Figure 7 shows settlement of ground surface during the model tunnel test. 8 curves appeared according to volume loss values (1.5%, 3%, 5%, 7%, 10%, 14%, 18%,

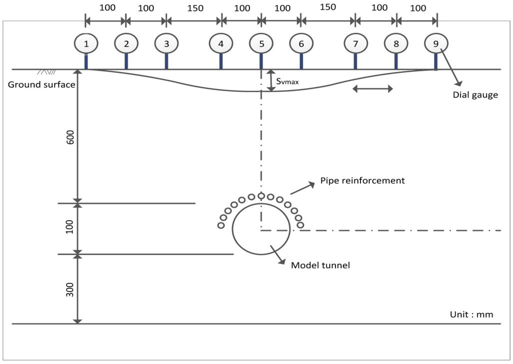

Figure 6. Measurement of ground surface using dial gauges in model test.

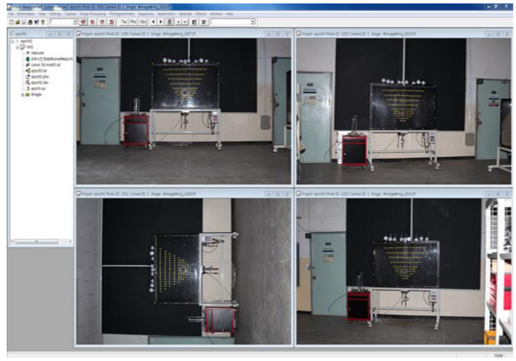

Figure 8. Measurement of target points using VMS program.

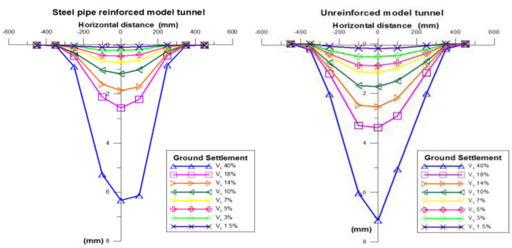

Figure 7. Settlement of ground surface during the model test.

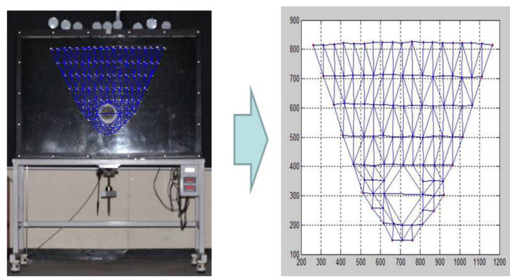

Figure 9. Generation of triangle mesh using EngVis program.

40%). The curves show the classic shape of a settlement. They appeared the development of the maximum settlement on the tunnel centre line. In general, the distributions observed are similar to Lee, 2009. From results of the steel pipe reinforced effect, surface settlement decreases about 12.5% compared to unreinforced model tunnel.

3 CLOSE RANGE PHOTOGRAMMETRY FOR MODEL TEST

3.1 *Test equipments*

The aluminium rod contained two diameters (5 mm and 6 mm) and a length of 100 mm. It represents a well idealized 2D granular material. The aluminium rods (φ 5 mm) were mainly used for target points in the model ground. It is noted that rods are assumed as the model ground. The aluminium rods (φ 6 mm) are represented for the steel pipe reinforced ground at tunnel crown level.

3.2 *Measurement of displacement within aluminium rods*

The close range photogrammetric technique was chosen to measure displacements because it is a useful non-intrusive method for studying deformation patterns being capable of resolving displacement to approximately 0.4 mm (Lee, 2012). Digital cameras can now provide acceptably high resolution. Four independent images were taken at each epoch using the digital camera. A pixel resolution of 5616 × 3744 pixel was available using digital camera (Canon EOS 5D Mark II). Each retro-reflective target was identified and the position of its image within each of the four photographs was measured by the VMS (vision metrology system) program (see Figure 8). The measured x-y coordinates of the target points from the VMS are arranged into a triangulation mesh by means of the EngVis program (see Figure 9). More details of the VMS program are available on a web site http://www.geomsoft.com/VMS/index.html.

3.3 *Image processing*

This chapter will discuss the behaviour of ground deformation subjected to tunnel excavation. The authors investigated the displacement patterns (vertical settlement, S_v, and horizontal displacement, S_h) and displacement vector. The ground deformation data, S_v and S_h were extracted from the vertical and horizontal displacement contours provided by the image processing.

Vertical displacement contour

The vertical displacement contours at the volume loss of 5%, 18% are represented for the unreinforced and steel pipe reinforcement model tunnel excavation in

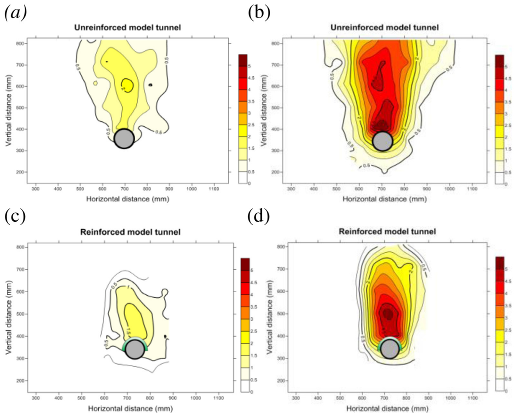

Figure 10. Comparison of vertical displacement contours for V_L, (a) $V_L = 5\%$, (b) $V_L = 18\%$, (c) $V_L = 5\%$, (d) $V_L = 18\%$.

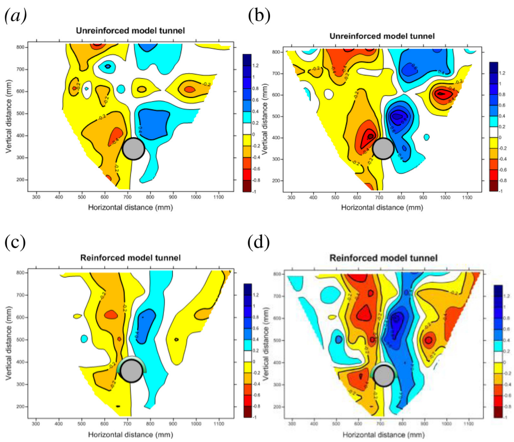

Figure 11. Comparison of horizontal displacement contours for V_L, (a) $V_L = 5\%$, (b) $V_L = 18\%$, (c) $V_L = 5\%$, (d) $V_L = 18\%$.

Figure 10. Clearly, a narrow 'chimney' type pattern of vertical displacement was observed.

Horizontal displacement contour

The horizontal displacement contours at the volume loss of 5%, 18% are shown in Figure 11 for the unreinforced and steel pipe reinforcement model tunnel excavation. A clear 'ear' pattern on both sides of the tunnel can be seen. The contours extend sharply upward from the tunnel invert level.

Displacement vectors

Figure 12 shows pictorially the physical x-y displacement vectors for unreinforced and steel pipe reinforced model tunnel excavation at the volume loss of 5%, 18%. The vector shows classic tunnelling deformations, the magnitudes reducing rapidly the further above the tunnel crown.

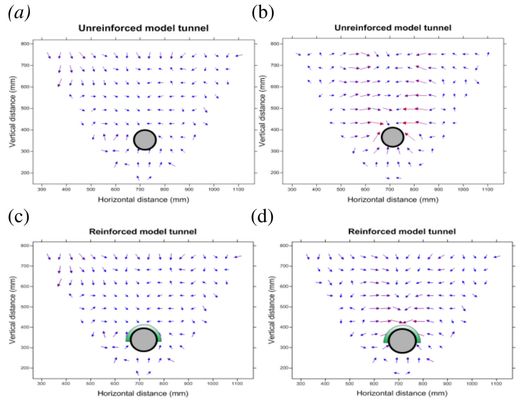

Figure 12. Comparison of displacement vectors for V_L, (a) $V_L = 5\%$, (b) $V_L = 18\%$, (c) $V_L = 5\%$, (d) $V_L = 18\%$.

Table 2. Input parameters in FE analysis of tunnel model test.

Parameters	Soil layer	Tunnel	
E (kN/m^2)	900	EA (kN/m)	1.4×10^7
C (kPa)	0.10	EI (kN/m^2/m)	1.43×10^6
ν	0.35	ν	0.15
Φ (°)	41.0	w (kN/m/m)	8.4
Ψ (°)	11.0	d (m)	0.3501
γ (kN/m^3)	16.5		
Parameters	**Reinforcement**		
E (kN/m^2)	606,939.6		
A (m^2)	0.1936×10^{-6}		

E: Young's modulus, c: Cohesion, ν: Poisson's ratio, Φ': Angle of shearing resistance, Ψ: Dilation angle, γ: Unit weight of soil.

4 FE ANALYSIS OF LABORATORY MODEL TEST

4.1 *FE analysis*

Chapter 4 describes ground behaviour subjected to tunnel excavation in FE analysis. In order to measure ground deformation through FE analysis, PLAXIS 2D are used. PLAXIS is a finite element package specifically intended for the analysis of deformation and stability in geotechnical engineering projects.

Analysis conditions

FE analysis of model tunnel test is carried out based on laboratory model test. This analysis is carried out in 2D plane-strain condition. Mohr-Coulomb model is applied for the soil, tunnel is modelled elastic model. Boundary of ground is dimensioned by the width of 1500 mm and depth of 1000 mm size. Tunnel is modelled by the diameter of 100 mm. The material parameters are summarized in Table 2.

(a) (b)

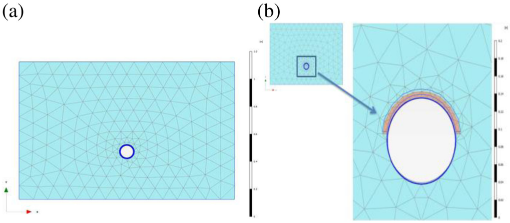

Figure 13. Comparison of deformed mesh ($V_L = 5\%$), (a) unreinforcement, (b) reinforcement.

(a) (b)

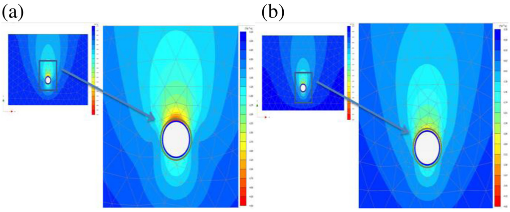

Figure 14. Comparison of vertical displacement contours ($V_L = 5\%$), (a) unreinforcement, (b) reinforcement.

Unreinforced model tunnel
In order to simulate the tunnel excavation, the contraction parameter is used. It can be used to simulate the volume loss in the soil due to the construction of the tunnel. The contraction parameter is defined as the reduction of the tunnel area as a percentage of the original tunnel area. The input value of the percentage (Volume loss, V_L) is 5% in all of the FE analysis.

Steel pipe reinforced model tunnel
In this study, ground deformation for steel pipe reinforced model tunnel is measured by 2D FE analysis. In 2-dimensional analysis, steel pipe reinforced assumed the area (Figure 13(b)). Ground reinforcement effect by reinforcement of steel pipe is difficult to measure. Therefore strength parameter of steel pipe reinforced ground is estimated using equivalent elastic method (see Kim, 1998).

4.2 *Results of FE analysis*

2D FE analysis
This chapter presented the 2-Dimensional FE analysis of model tunnel test. The author presents the detailed output data from FE analysis (d_x and d_y displacements as vectors and contours). After FE analysis, deformed mesh for reinforcement is appeared (Figure 13). Results of FEA show the vertical, horizontal displacement contours and displacement vectors for reinforcement (Figures 14 to 16). Likewise with the image processing, the contours and vectors show the classic tunnelling deformations. But distribution of ground deformation shows considerably more extensive. This results are presumably due to the constant ψ value for the soil properties.

(a) (b)

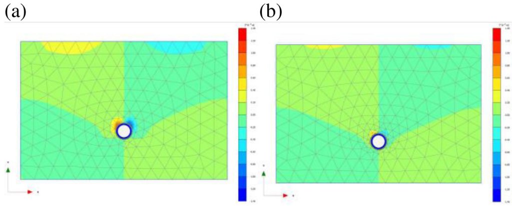

Figure 15. Comparison of horizontal displacement ($V_L = 5\%$), (a) unreinforcement, (b) reinforcement.

(a) (b)

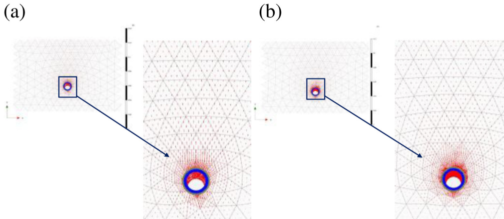

Figure 16. Comparison of displacement vectors ($V_L = 5\%$, MF: 10), (a) unreinforcement, (b) reinforcement.

(a) (b)

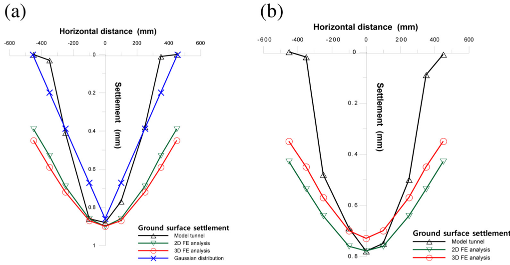

Figure 17. Comparison of settlements of ground surface ($V_L = 5\%$), (a) unreinforcement, (b) reinforcement.

Comparison of ground surface settlement between FE analysis and model test
For comparative purposes between the numerical and physical models, the author used the settlement data of ground surface. Maximum settlement of ground surface is accurately predicted by gaussian distribution. So, it compared to model tunnel test and FE analysis. The assumed Gaussian error function associated with i values appear to fit the surface settlement data up to a horizontal distance of 2.5i in both the finite element analysis and the laboratory model tunnel test. Figure 17 shows settlement of ground surface for reinforcement ($V_L = 5\%$). The curves show the classic shape of a settlement. They appeared the development of the maximum settlement on the tunnel centre line. In general, the distributions observed are similar to the model tunnel test data for FE analysis and Gaussian distribution. But settlements of ground surface show considerably more extensive in FE analysis. This results are presumably due to the constant ψ value for the soil properties. From the results of steel pipe reinforced effect, surface settlement decreases about 11%

in model tunnel test, about 19% in 2D analysis, about 13% in 3D analysis.

5 CONCLUSION

The authors have investigated ground behaviour due to the model tunnel excavation in the laboratory model test. The close range photogrammetry technique was used to measure the ground deformation. A comparative study between the FE analysis and the physical model test was carried out. The study showed that, in general, the FE analysis could be validated by the physical model tests.

1) The soil deformation patterns (vertical displacement, horizontal displacement, displacement vector) from image processing are compared quite well with the physical model tests.
2) The measurement of the aluminium rods represented for the target points in the black sand by close range photogrammetry provides reliable and accurate displacement data. These displacements can be conveniently analysed to provide quantitative data.
3) According to results of FE analysis and image processing, the formation of a classic settlement trough was observed. The “chimney” pattern of vertical displacement and the “ear” pattern of horizontal displacement contours were observed. The vectors of displacement were appeared to point towards the tunnel invert.
4) Comparison between the physical model test and the finite element analysis showed many successful points of agreement, and reasons for deviations have been identified. In particular, the finite element analysis could be validated by the model test.

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REFERENCES

Kim, C. Y., Bae, G. J., Moon, H. K., Choi, Y. K. and Choi, Y. K. (1998), “A Study on the Three Dimensional Finite Element Analysis for the Tunnel Reinforced by Umbrella Arch Method”, J. of Korean Society for Rock Mech., Tunnel & Underground, Vol. 8, 1998, pp. 209–225.

Lee, Y. J., Bassett, R. H. (2006). “Application of a photogrammetric technique to a model tunnel”, Tunnelling and Underground Space Technology 21 (3–4), 370.

Lee, Y. J., Yoo, C. S., (2006). “Behaviour of a bored tunnel adjacent to a line of loaded piles”, Tunnelling and Underground Space Technology 43 (2), 315–320.

Lee, Y. J., Bassett, R. H. (2006). “A model test and numerical investigation on the shear deformation patterns of deep wall-soil-tunnel interaction”, Canadian Geotechnical Journal 43, 1306–1323.

Lee, Y. J. (2009). “Investigation of subsurface deformations associated with model tunnels in a granular mass”, Tunnelling and Underground Space Technology 24, 654–664.

Lee, C. N., Oh, J. H. (2012). “A Study on Efficient Self-Calibration of a Non-Metric Camera for Close-range Photogrammetry”, Journal of Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 30, Vol. 6–1 pp. 511–518.

Lee, C. N., Oh, J. H. (2013). “Measurement of Soil Deformation around the Tip of Model Pile by Close-Range Photogrammetry”, Journal of Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 31, Vol. 2, pp. 173–180.