Integrating Artificial Intelligence for Enhanced Tunnel Convergence Monitoring: "A Paradigm Shift from Total Station to Pose Estimation Algorithm"

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Abstract

Tunnel collapse is a significant risk in tunnel both during construction and operation. Tunnel deformation monitoring, so called tunnel convergence monitoring, play an important role in giving early warning signal to engineers to review the safety and making decision to strengthening of tunnel support. Several methods for monitoring tunnel convergence include Total Station, Prism-based monitoring, and Wireless Sensors Networks, 3D Laser Scanning and Photogrammetry, the use of total station to measure the positions of optical targets has been, and still be, the dominant method for tunnel convergence monitoring, because it is already utilized in typical construction for survey control network and alignment control of the tunnel itself. Nevertheless, there are some limitations, and interfere with on-going construction activities. The reference points for total stations requires periodic maintenance due to damages, misplaced by construction activities, or dynamic deformations over time of tunnel itself, which requires tremendous efforts in interpretation of survey data to ensure reliability. To overcome the problem presented in Total Station method, the new method with the integration of Artificial Intelligence (AI) using pose estimation algorithm to identify and locate the fiducial markers for its position in 3 dimensional spaces will be presented. The relative distances between markers are calculated and compared with the initial reading data to identify the degree of deformation of the tunnel. Both in-lab and in-field experiment were performed to compare the proper environment for the camera to detect and extract visual data, and sensitivity of the camera to detect small degree of movement.

Keywords: Pose Estimation, Tunnel Convergence, Computer Vision, Fiducial Markers, Engineering Institute of Thailand, National Convention on Civil Engineering.

1. Introduction

The Construction of Den Chai-Chiang Rai-Chiang Khong Railway Project is a new double-track railway project of total distance approximately 325 kilometers. The project's infrastructure comprises 26 railway stations, 4 railway tunnels, 40 overpasses and 102 underpasses, under development by State Railway of Thailand (SRT). The selected route has many challenges as it goes through mountainous terrain of the northern part of Thailand.

Mae-Ka Tunnel is one of the challenged railway tunnel, designed to be constructed using NATM Method. The underground condition is completely weather rock and soil throughout the 2.7 kilometers. The twin tunnels are intermittently connected by cross passageway and large equipment room for safe evacuation and housing the life-safety equipment. The tunnel convergence monitoring play an important role in risk control during construction and give early warning to engineer to strengthen the support in poor ground condition.

The total station is the common tools used in construction sites to provide setting point read from the drawing, elevation, and alignment for construction. Thus, it is often the first choices among other methods due to its availability on site and familiarity by the construction people as a tool to determine the Tunnel Convergence. However, the use of total station has some shortfall such as interference by construction activities to the target attached to the tunnel wall, movement of reference monument served as stationary reference point, and timely preparation of result of the survey measurements which need to convert the survey data into position of target in Cartesian coordinate, etc.

The use of fiducial markers and computer vision to monitor tunnel convergence is a novel approach. It can offer several

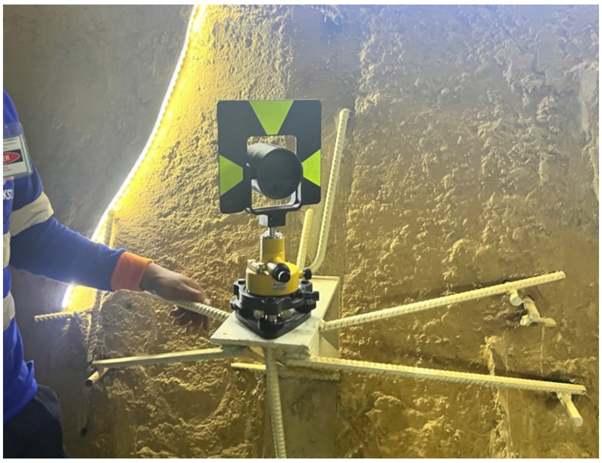

Figure 1 Reference Monument mounted on bracket attached to Tunnel's wall

Figure 2 Target for Convergence Monitoring by conventional method

benefits such as integration with AI to analyze the muti-dimensional measurement data, integration with IoT for automatically acquiring the data and enriched spatiotemporal data for dynamic analysis. It is low cost comparing to other automated systems such 3D Laser Scanning or conventional method of using total station.

In this paper, the potential use of fiducial marker and computer vision to monitor the tunnel convergence will be explored. The set up will be in both laboratory in which the fiducial marker movement is controlled and in field to test with actual environment. The objective of this paper will focus on the demonstration of novel computer vision method comparing to conventional method in off-line monitoring.

Figure 3 Fiducial Marker for monitoring at equipment room

2. Methodology

2.1 Apparatus

The fiducial marker and computer vision are an interdisciplinary field that combines principles from engineering, computer science. The fiducial marker or so-called tracking marker is embedded with low-bit data which is marker's ID for computer vision to be able to recognize and apply algorithm on data retrieve from each marker.

2.1.1 Fiducial Marker

The fiducial marker serves as target for computer vision to detect and tracking. It has different of high-contrast patterns for easily recognizable by computer vision algorithms and

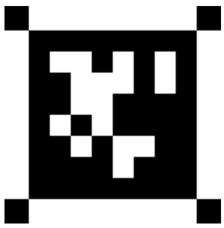

Figure 4 April Tag Marker "0"

embedding with numerical data. In this paper, the "AprilTag" will be used. Each marker has its own orientation which is defined by the face patterns. The orientation of the camera is independent and will change with respect to the world coordinate if the camera is moving. The *Figure 6* explains the marker axis which are independent and may not necessarily be aligned with camera's axis. The world coordinate may be chosen to align with one of the markers and used as reference coordinate system for other markers.

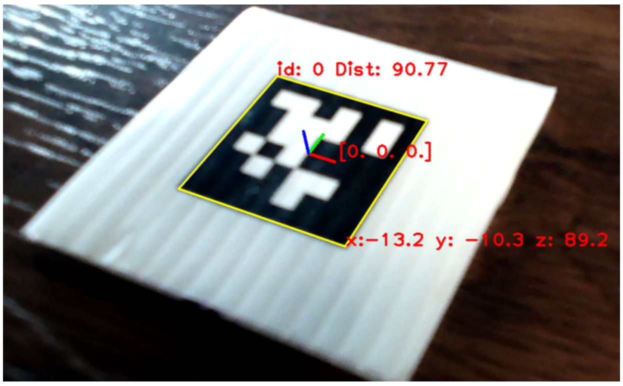

Figure 6 Coordinate of AprilTag x-axis (red), y-axis(green) and z-axis(blue)

2.1.2 Software and Hardware

OpenCV, short for Open-Source Computer Vision Library is an open-source computer vision and machine learning software library. The code is developed in Python and can be run on personal laptop computer or raspberry Pi, which provide low-cost solutions.

2.1.3 Accuracy and Sensitivity

The accuracy of reading depends mostly on the resolution of camera, distance to the marker, and size of the marker. The relationship between camera resolution and accuracy of reading would not be discussed in this paper. The maximum distance to marker size ratio for the camera used in this study was found not exceed 20 for reliable result. This is based on resolution of typical HD web cam.

2.2 Calculations

The PnP (Perspective-n-Point) algorithm is used for estimation of marker position and its orientation. It requires camera to be calibrated for intrinsic parameters and combine with input data from 2D image to estimate the pose (translation and rotation of object relative to camera).

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1\,0\,0\,0 \\ 0\,1\,0\,0 \\ 0\,0\,1\,0 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

Equation 1 Transfer Coordinate Equation using pin hole model

2.2.1 Random Variables

The choice of random variable is very much importance as each random variable may explain the dynamic behavior of the system better than another. To compare with the conventional method (total station) the position of fiducial marker will be stored in Cartesian coordinate system with respected to selected reference marker (marker "0") not respect to fixed camera's position.

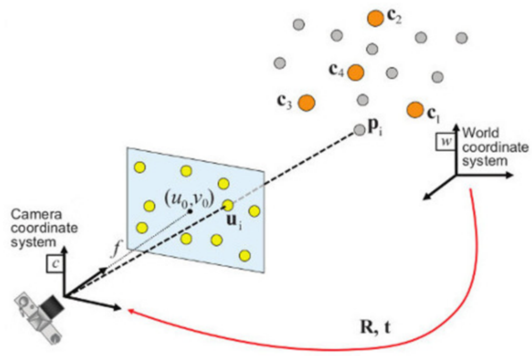

Figure 5 Camera Coordinate System and World Coordinate System [1]

The initial reading will be used as a reference for comparison with subsequent reading. With known parameters from calibrated camera, the computer vision use algorithm to estimate the position of each marker based on the perspective view that camera see, while the position of the camera of computer vision can be moving or stationary without changing the coordinate data of the markers.

The distance between each pair of nodes will also be collected as separate set of random variables for comparison with the result from coordinate data.

Figure 7 Main Tunnel from North Portal of Mae – Ka Tunnel

2.3 Evaluation and Detection of Moving Marker

In tunnel convergence monitoring, the movement of ground during tunnel excavation is considerably slow, thus data collection period can be varied initially daily and weekly subsequently as the tunnel face move away from the monitored section [2].

The requirement on accuracy of tunnel convergence is prime concerned and will be investigated under controlled environment.

Finally, the displacement of each marker at different period will be compared with the initial reading and compare with the prediction from numerical model.

2.3.1 Hypothesis Testing (Frequentist Statistical Approach)

The data of coordinate x, y, z of each marking using marker "0" as reference for world coordinate are collected. The data is repeatedly collected at different camera position and using hypothesis testing with 95 % confident interval to confirm and reject null hypothesis.

To reduce the dimension of data for ease of performing the statistical testing, the Euclidean distance between each pair of nodes will be calculated from the x, y, z coordinate.

$$\Delta_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Equation 2 Euclidean Distance from Node 1 to Node 2

Null Hypothesis (H_0): The distance is not statistically different from the initial reading (reference); therefore, the marker is not moving.

Alternative Hypothesis (H_1): The distance is statistically significant different from the initial reading (reference); therefore, the marker is moving.

Interpretation of the result, if the p-value is less than the significance level (α = 0.05), the null hypothesis will be rejected, suggesting that the marker is indeed moving supporting by statistical evidence, or if the p-value is greater than the significance level, the null hypothesis cannot be rejected, indicating that insufficient evidence to conclude that the marker is moving.

The evaluation by using hypothesis testing prone to have false negative unless data collection involves many angles of camera and distance from camera to target.

2.3.2 Time History Plot Analysis

Interpretation of Tunnel convergence needs also time historical data. To better representation of displacement versus time, the distance between pairs of markers will be normalized to its initial reading and plot against period from the initial reading. The data will be recorded as a vector between two markers which represent both size and direction. To represent both changes in size and direction of the vector between two markers, the cosine similarity matrix is introduced and can be calculated using the following equation.

$$Cosine\ Similarity = \frac{\vec{A}.\vec{B}}{\|A\|\|B\|}$$

Equation 3 Cosine Similarity

Where:

- A · B represents the dot product of vectors between markers between same pair of markers at time t and t+Δt
- ||A|| and ||B|| represents the magnitudes (or lengths) of vector A and B respectively.

The cosine similarity can capture the change of vector between two markers of both size and direction, in contrast to the conventional method which only capture of change in distance (length of vector in term of percentage of chord length between two markers).

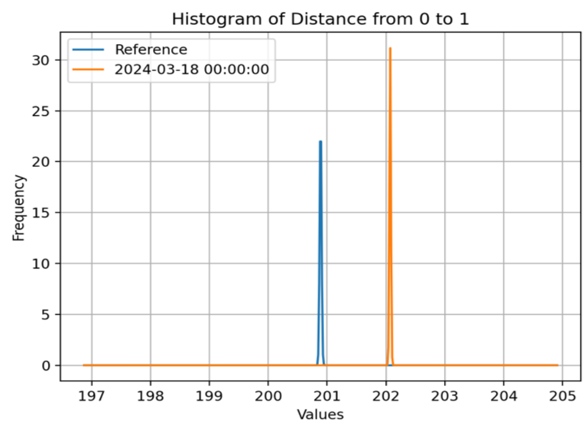

Figure 8 Hypothesis Testing using hypothesis testing

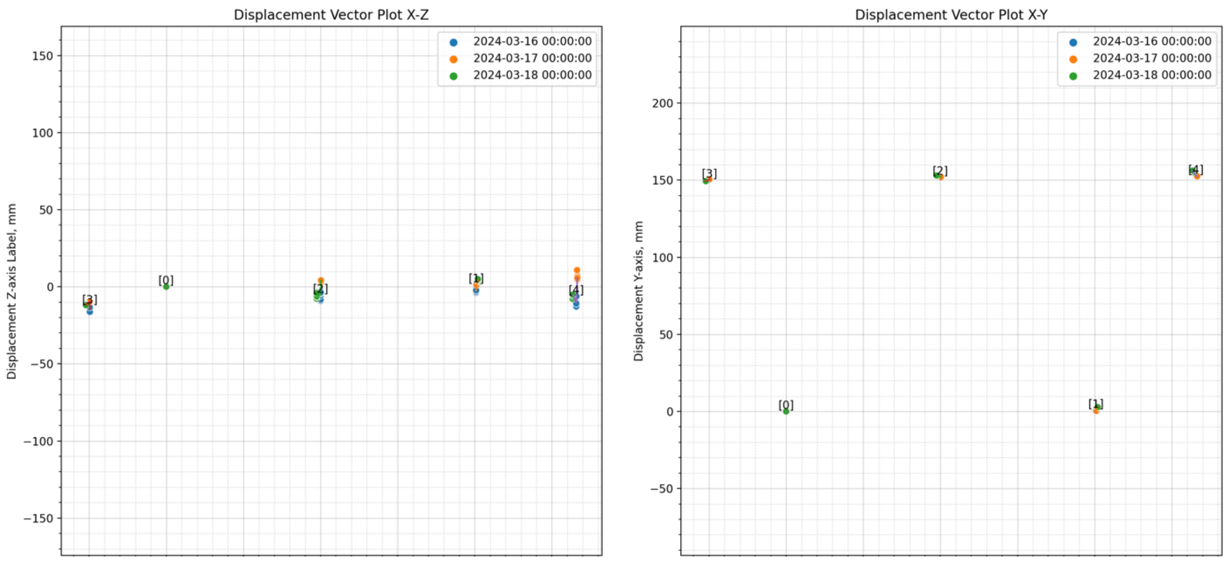

Figure 9 Scatter Plot of marker in X-Y and X-Z Coordinate at different period

3. Testing

3.1 Accuracy Testing

The small-scale mockup is setup for testing of repeatability and resolution of detection algorithm by intentionally moving the marker and comparing to its various original measurements.

3.1.1 Configuration

The small markers are arranged at the location as same as where typically found in Tunnel monitoring but smaller scale. The distance between marker “0” and “1 is 200 millimeters.

3.1.2 Procedures

The test was performed in three steps at controlled ratio of distance to marker’s size of 15. The first and second step is to test the repeatability which the test will be conducted independently several times without moving the markers. The plot of each markers in cartesian coordinate will be plotted and compared with the tape measurement.

The third step, marker no.1 will be intentionally moved by 0.5% (1 mm) of the distance between marker 0 and 1 to check if the algorithm could detect the small movement as required by the design.

3.1.3 Results

The time-history vector plot of markers often use to confirm the trace of tunnel deformation. As the reading contains error therefore the pattern of movement will exhibit the same. Unless the time-history vector plot explicitly show development of trend of moving markers, but the tunnel will already experience excessive movement without wall strengthening.

The marker number “1” was intentionally move by 0.5% of distance relative to marker “0” but the other markers remain untouched. From the time-history vector plot alone, it is very difficult to detect the movement, while the zigzagging pattern of other markers movement represent the error of reading (Figure 9).

p-Value

The statistical testing approach was applied in attempt to find evidence to support if markers indeed moved. The hypothesis testing can identify the 0.5% movement of distance between marker “1” with respect to marker “0” as shown in

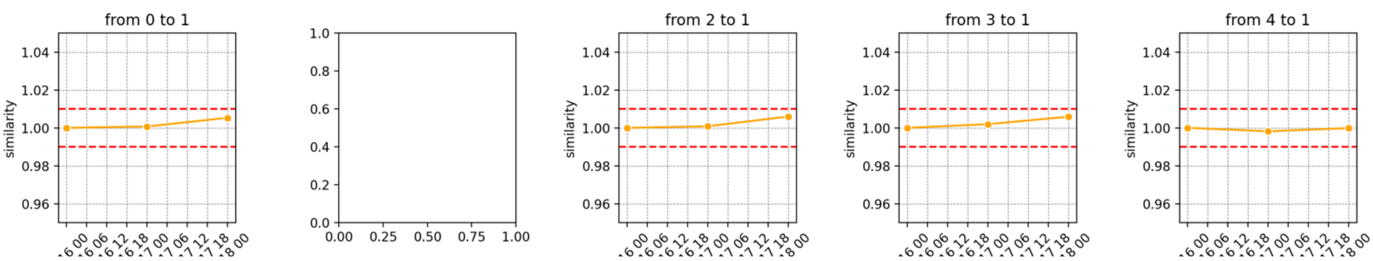

Figure 10 Cosine Similarity

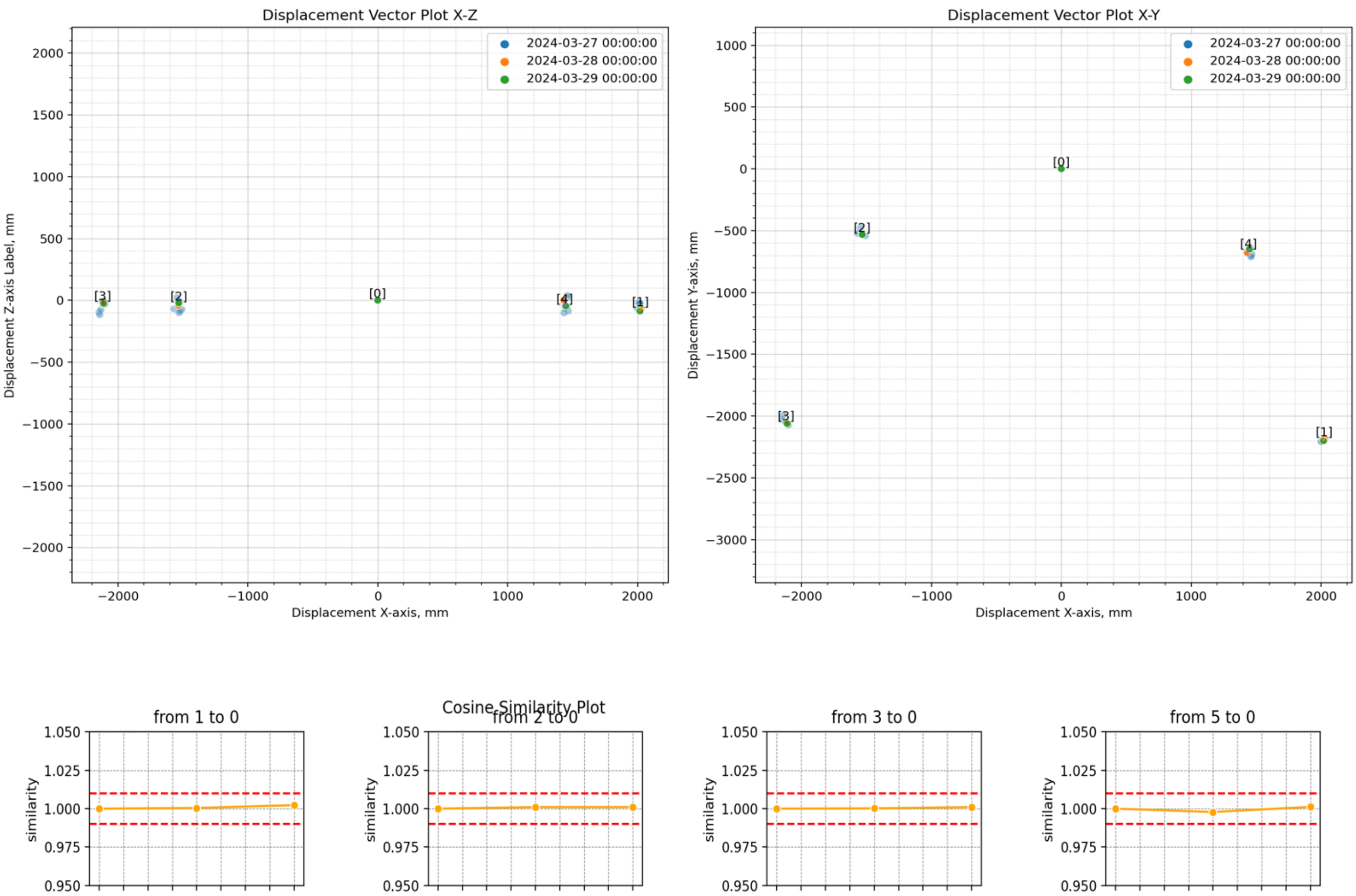

Figure 11 Time-History Vector Plot of marker movement (Upper) Cosine-Similarity Plot of Full Scale Mockup (Lower)

Figure 8. However this method may also yield false negative (identify moving while it is actually not move).

Cosine-Similarity

The cosine similarity measure the similarity of vectors between two markers and compare with the its initial value for comparison both in length and angle. The cosine-similarity is normalized by the length of initial vector. This method capture both movement of markers and also change in direction. The result in Figure 10 suggest that marker number 1 is moving comparing to marker 0, 2, 3, and 4. It should notice that even the fact that marker 1 is actually move, but it may not significantly noticeable to review against single marker 4 as the movement is tangent to vector $\overrightarrow{14}$.

3.2 Full Scale Mockup

3.2.1 Configuration

A full scale tunnel cross passage was set up, for testing with 150 mm marker to review the accuracy of reading given actual size of reference frame and camera angle.

3.2.2 Procedures

The test was performed without moving the markers. This is to confirm if the reading of three different positions of camera will yield consistency result for interpretation and conclusion of tunnel convergence.

3.2.3 Results

The time-history vector plots of markers exhibit certain degree of consistency as the position of each markers are clustered together as shown in Figure 11.

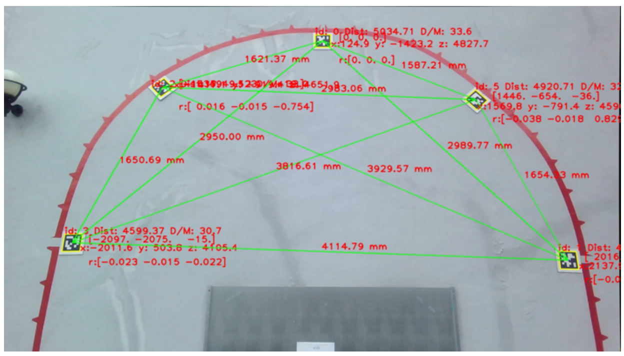

Figure 12 Reading of markers and collected data on screen

The cosine similarity matrix of distance of each marker with respect to marker "0" exhibit the similar result which the difference fall within the tolerance of 1%. The cosine similarity plot also exhibit the trend if the tunnel convergence is actually moving.

3.3 North Portal Down Track – Main Tunnel

3.3.1 Geological Condition

The rock types through the tunnel route were generally Sedimentary Rocks and Unconsolidated Sediments. The sedimentary rocks are Pha Daeng formation, consisting of siltstone, sandstone and conglomerate, brown to reddish-brown in color, thin to thick bed. It is predominantly medium-strong as classified by International Society for Rock Mechanics, ISRM (1981) [3] for fresh to slightly weathered stage. The unconsolidated sediments consist of sandy-silty clay with gravel and pebble of rock fragments, yellowish-brown and reddish-brown in color. They are extremely weak rock as classified by ISRM (1981) [3]. The distribution of rock types along the tunnel can be summarized in *Figure 16*.

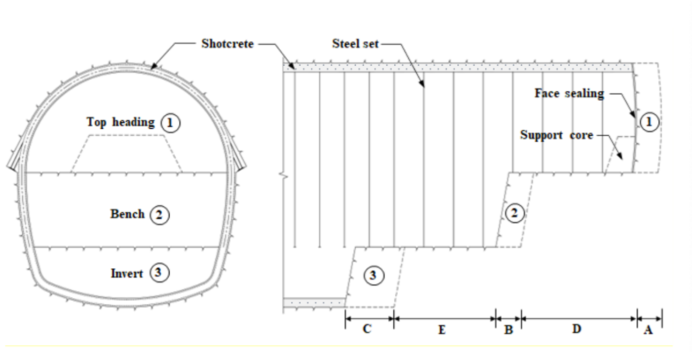

Figure 13 Construction Sequence [4]

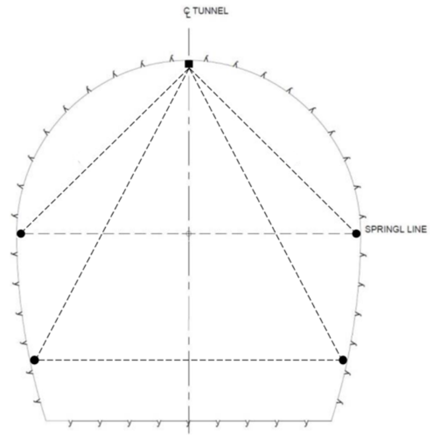

Figure 15 Convergence Monitoring Layout [4]

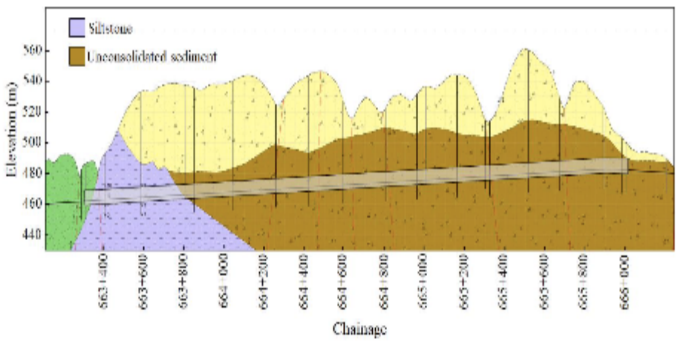

Figure 16 Longitudinal profile of geology along the tunnel alignment

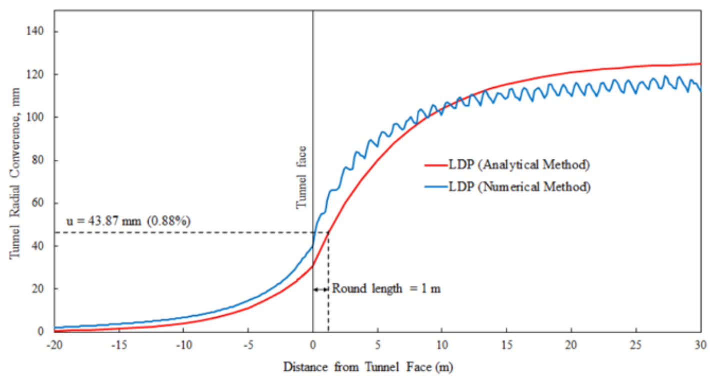

Figure 14 Longitudinal Displacement Profile (LDP) for unconsolidated sediment [4]

3.3.2 Construction Sequence and Convergence

The convergence of tunnel depend not only on the ground condition but also construction sequence. The tunnel excavation has three stages which are top heading, bench and invert for unconsolidated sediment. After full face excavation, the combination of shotcrete and steel rib is predominantly used as temporary support .

Convergence monitoring of Tunnel layout is specified to monitor the ground movement at crown, spring line and bench/invert as depicted in Figure 13.

The estimated convergence of tunnel after excavation was performed using Analytical analysis and Numerical Analysis whose result is estimated in Figure 14.

At the time of collecting the data, the tunnel-face forward the test section further than 400 m, therefore the movement of convergence is not expected.

3.3.3 Monitoring result by Conventional Total Station

The convergence by conventional method uses the total station to measure the coordinate of marker layout as shown in Figure 17. The change in distance was calculated as percent strain compared to its initial reading. The time history data of convergence strain measured as percent different in length compared to initial reading.

The reading by total station relies on the reference monument which refers its coordinate from the outside of the tunnel. As the tunnel goes deeper into the ground, the more reference monument will be installed due to the line of sight of camera. The best position for these monuments is temporary tunnel lining as it less interferes with construction equipment and risk of moving by construction activities. But the temporary tunnel lining itself also not stable, thus requires these monuments frequently recalibrated.

The typical zigzagging pattern Is usually found due to the reading error and movement of the reference point.

3.3.4 Monitoring result by Computer Vision

The period of recording the data was done after the tunnel face move further away from the tested section. From the analysis, it is anticipated that the convergence should not moving.

The cosine similarity plot suggest the movement is found within 2% of the distances between marker as required in the design criteria (1-2% of tunnel diameter) as shown in Figure 18.

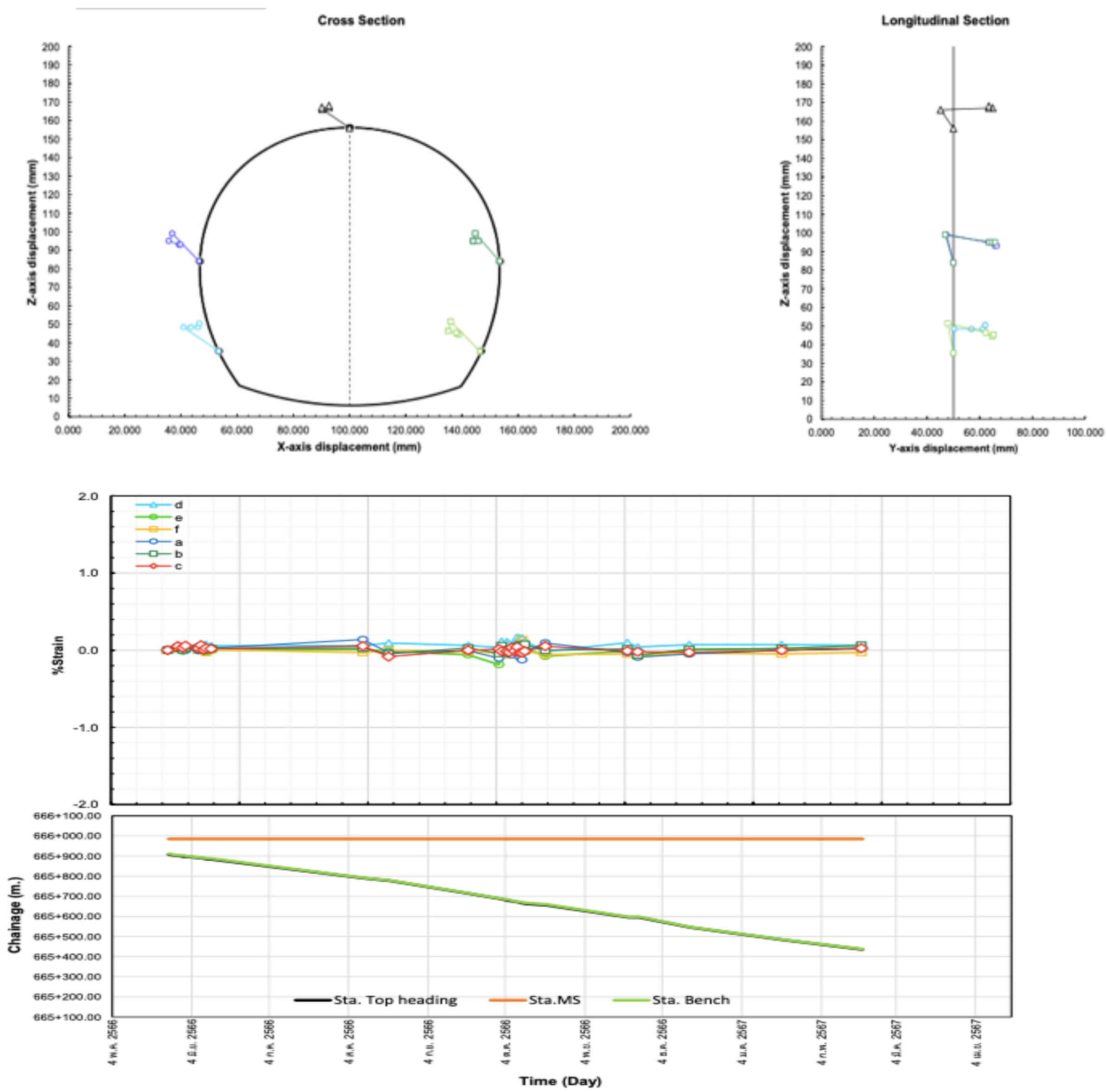

Figure 17 Time History plot of % change in length by Conventional Method

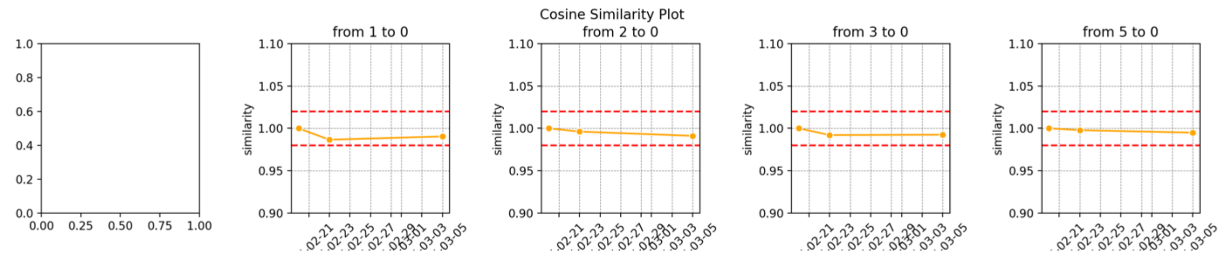

Figure 18 Cosine Similarity Plot of data from Tunnel (North Portal)

4. Conclusions

Tunnels are indispensable in modern infrastructure development, offering solutions to efficient transportation and resource utilization. The advancement in tunnel construction have been driven by technological innovation and quest for more efficient, safer, and environmentally friendly methods. Regular monitoring of tunnel convergence during construction is deemed necessary as preventive measures to prevent loss of life and avoid delay of construction. Traditional methods often rely on manual using conventional construction survey tools which can be interfered by construction activities and required timely preparation of report and interpretation.

The measurement obtained from the total station are affected by systemic errors stemming from the movement of the reference point and reading inaccuracies, as indicated in the report where the target appears to drift unpredictably. This situation poses a challenge for engineers when making decisions, often leading to inconclusive results, and rendering decision-making difficulty.

A novel approach using computer vision provide enriched spatiotemporal data for more complex evaluation method and seamlessly integrating with AI which also offer solution to on-line monitoring and on-site warning system. The on-line monitoring has been a challenge and many methods have been explored but mostly in aspect of hardware, not in realm of AI algorithm in making decision.

The radial convergence was estimated approximately 1-1.5% of tunnel diameter, and the warning limit was set at 1-2%. The standard deviation of measurement reading using computer vision is approximately 0.1% – 0.5% of the measured length or less if the distance to marker size ratio is lower than 15, which is sufficient for use in this application.

The use of computer vision together with evaluation method demonstrating in this paper can be adapted to work with AI for on-line and off-line monitoring as well as on-site warning system because the evaluation could be performed automatically instantly on site. Several evaluation matrices can also be deployed using the dataset collected by computer vision.

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