An Enhanced Convergence Monitoring by Computer Vision in NATM Construction

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ABSTRACT: Geodetic surveys are widely employed in tunnel convergence monitoring to ensure safety and provide data for optimizing tunnel support. Tunnels in weak rock are particularly prone to ground squeezing, making convergence measurements critical for informing adaptive support strategies, especially in NATM construction where design adjustments are made to suit site-specific conditions. Traditional geodetic measurements guide support modifications, such as rock bolt installation and spacing adjustments, but they conflate structural deformation with global tunnel translation. For example, bottom heave may lift the tunnel crown while ground squeezing pushes it downward, resulting in a net movement that masks true structural strain. Unlike structural deformation, which generates internal stresses and can overstress or buckle steel ribs, global translation does not affect support forces. This study proposes a computer vision–based method to measure pairwise distances relative to an initial reference frame. Utilizing a novel interconnecting pairwise distance algorithm, the method registers corresponding points across monitoring periods and separates actual deformation from global translation. This approach enables precise tracking of strain and allows engineers to optimize steel and rock bolt reinforcement placement based on accurate deformation data.

KEYWORDS: Computer Vision, Deformed Point Registration, Tunnel Convergence, and NATM Method.

Introduction

Monitoring tunnel deformation is a critical aspect of ensuring stability and safety during construction, especially in weak rock conditions. In the New Austrian Tunneling Method (NATM), tunnel support design is intentionally flexible, allowing engineers to adapt support systems, such as rock bolts, shotcrete, and steel ribs, in response to actual ground behavior. Accurate and timely monitoring of tunnel convergence is therefore essential for maintaining structural integrity and optimizing support.

Traditionally, geodetic surveys have been the primary tool for measuring tunnel deformation. These surveys use total stations or laser theodolites to measure precise 3D positions of control points along the tunnel lining over time. Geodetic monitoring provides a cost-effective and proven method for tracking tunnel convergence, crown settlement, and sidewall deformation. However, it has several limitations: measurements are often discrete, labor-intensive, and limited to predefined points; they can be affected by human error and instrument stability; and they typically combine true structural deformation with global tunnel translation, making it difficult to isolate the stresses acting on support systems.

Recent advances have introduced mobile laser scanning (MLS) as a complementary or alternative monitoring approach. MLS systems can rapidly capture dense 3D point clouds along the tunnel surface, providing detailed geometrical information over continuous surfaces rather than discrete points (Sun et al., 2020). This allows for a more comprehensive assessment of tunnel shape, deformation patterns, and volume changes. Despite these advantages, MLS also presents challenges: the high volume of data requires substantial post-processing and registration; maintaining accuracy in narrow or poorly illuminated tunnels can be difficult; and distinguishing between structural deformation and overall tunnel movement remains non-trivial.

The proposed approach integrates computer vision techniques with fiducial markers affixed to the tunnel lining to accurately capture spatial information. By detecting these markers in images, the system computes pairwise distances, which inherently encode the spatial relationships among the markers.

These distances are subsequently transformed into Euclidean coordinates using Multidimensional Scaling (MDS), converting the distance-based representation into a coordinate-based representation in Euclidean space. Compared to traditional surveying methods, this approach enables rapid, non-contact, and high-resolution reconstruction of the tunnel lining's geometry, facilitating precise monitoring and analysis of tunnel deformation and convergence. Its implementation offers a practical, less expensive in hardware and data management compared to MLS, and efficient solution for modern tunnel construction and maintenance, particularly under challenging or confined conditions.

Methodology

The fiducial markers, AprilTag or ArUco, embedded with unique identification numbers are placed at the point of interest. The open-source OpenCV framework is used for image analysis and retrieved data extracted from 2D images and performed pose estimation, which involves figuring out the position and orientation of markers in 3-dimensional space. This can be achieved with a single mobile phone camera (4K) resolution.

Point registration

The alignment of two set of points with known correspondences can be computed analytically using standard [R, T] transformation, where R is rotation and T is translation. Deformation refers to the relative movement of points while the centroid remains unchanged, whereas translation represents the global displacement of all points in the same direction. These two components must be addressed separately: deformation can be extracted using a novel algorithm for aligning deformed point sets, while translation can only be recovered when certain points are identified as stationary. The transformation can be expressed as:

$$\mathrm{P} = (\mathrm{Q} \, * \, \mathrm{R} + \mathrm{D} + \mathrm{T})$$

where:

$\mathbf{P} \in \mathbb{R}^{\mathrm{N}x3}$ is a target position matrix,

$\mathbf{Q} \in \mathbb{R}^{\mathrm{N}x3}$ is a point position matrix,

$\mathbf{R} \in \mathbb{R}^{3x3}$ is a rotation matrix,

$\mathbf{D} \in \mathbb{R}^{3x3}$ is a deformation matrix,

$\mathbf{T} \in \mathbb{R}^{1x3}$ is a translative vector (broadcasted across all points)

In geotechnical engineering, deformation of tunnel linings induces internal strains, whereas pure translation does not. Therefore, tracking deformation is crucial for structural assessment. This paper proposes a point registration algorithm that isolates deformation from overall movement. The method reconstructs target point coordinates using pairwise distances via Classical Multidimensional Scaling (MDS), which preserves relative distances while remaining invariant to translation and rotation. Displacements are then determined by registering reconstructed coordinates against either the previous monitoring period (temporal analysis) or the initial reference period (static analysis).

Interconnecting Distance Embedding (IDE)

The novel algorithm uses the differential of pairwise distance of points P and Q as the objective function in optimization.

$$\{ P_1, \, P_2, \, \ldots, P_n \}$$

$$\{ Q_1, Q_2, \, \ldots, Q_n \}$$

Each node P_i, Q_i are in spatial coordinates:

$$[\, P_i = \left(x_i^{(0)}{}_{i}, y_i^{(0)}, z_i^{(0)} \right) \,] \text{, (o-original)}$$

$$[\, Q_i = \left(x_i^{(d)}, y_i^{(d)}, z_i^{(d)} \right) \,] \text{, (d -deformed)}$$

Interconnecting pairwise distance before and after deformation,

$$\Delta_{ij}^{(o)} = \|P_i - P_j\|$$

$$= \sqrt{\left(x_i^{(o)} - x_j^{(o)}\right)^2 + \left(y_i^{(o)} - y_j^{(o)}\right)^2 + \left(z_i^{(o)} - z_j^{(o)}\right)^2}$$

$$\Delta_{ij}^{(d)} = \|Q_i - Q_j\|$$

$$= \sqrt{\left(x_i^{(d)} - x_j^{(d)}\right)^2 + \left(y_i^{(d)} - y_j^{(d)}\right)^2 + \left(z_i^{(d)} - z_j^{(d)}\right)^2} \;]$$

$$\Delta_{ij} = \Delta_{ij}^{(d)} - \Delta_{ij}^{(0)}$$

Since there are n nodes, the total number of node pairs is:

$$[\; m = \binom{n}{2} = \frac{n(n-1)}{2} \;]$$

Thus, the IDE forms an m-dimensional vector:

$$\Delta = \left[\Delta_{12}, \Delta_{13}, \Delta_{14} \ldots \Delta_{(n-1)n}\right]$$

The pairwise distance of P and Q are known from the direct measurement by computer vision. The IDE can also be approximated by summing the dot products of the displacement vectors of corresponding nodes to the unit vectors connecting them.

Each node P_i transitions from its original undeformed state to a deformed state, Q_i. The displacement vectors are defined as:

$$\vec{d}_i = Q_i - P_i$$

$$\vec{d}_j = Q_j - P_j$$

When the displacement vector, $\vec{d}_i$ moves in the same direction as the unit vector $\overrightarrow{v_{ji}}$ (pointing from node *j* to node *i*), the dot product will be positive, leading to an increase interconnecting length δ_{ij}.

The unit vectors are given by:

$$\overrightarrow{v_{ji}} = \frac{Q_i - Q_j}{\|Q_i - Q_j\|}$$

$$\overrightarrow{v_{ij}} = \frac{Q_j - Q_i}{\|Q_j - Q_i\|}$$

The total change in the interconnecting length between node *i* and node *j* is computed by summing the dot products at both ends:

$$\delta_{ij} = \vec{d}_i \cdot \overrightarrow{v_{ji}} + \vec{d}_j \cdot \overrightarrow{v_{ij}}$$

A positive δ_{ij} value shows extension, while a negative value signifies contraction. This results in an *m*-dimensional vector representation:

$$\delta = \left[\delta_{12}, \delta_{13}, \delta_{14} \ldots \delta_{(n-1)n}\right]$$

Optimization

Because the point P and Q share the same centroid. To align two set of points with known correspondences. The optimization for rotation matrix, R subject to the objective function below:

$$\min_R \sum_{i=1}^{n} (\Delta_i - \delta_i)$$

The global translation shall be aligned using objective function below:

$$\min_{T} \sum_{i=1}^{n} \sum_{j=1}^{3} \left(\alpha * \left| \left(Q_i^{(d)} R + t \right)_j - P_{ij}^{(o)} \right|_1 + \beta * \left\| \left(Q_i^{(d)} R + t \right)_j - P_{ij}^{(o)} \right\|_2 \right)$$

The deformation, D can be found by:

$$D = (P - Q * R)$$

Simulation

The simulation emulates the tunnel environment by applying convergence displacements to all markers, replicating the deformation behavior of the tunnel lining under operational conditions.

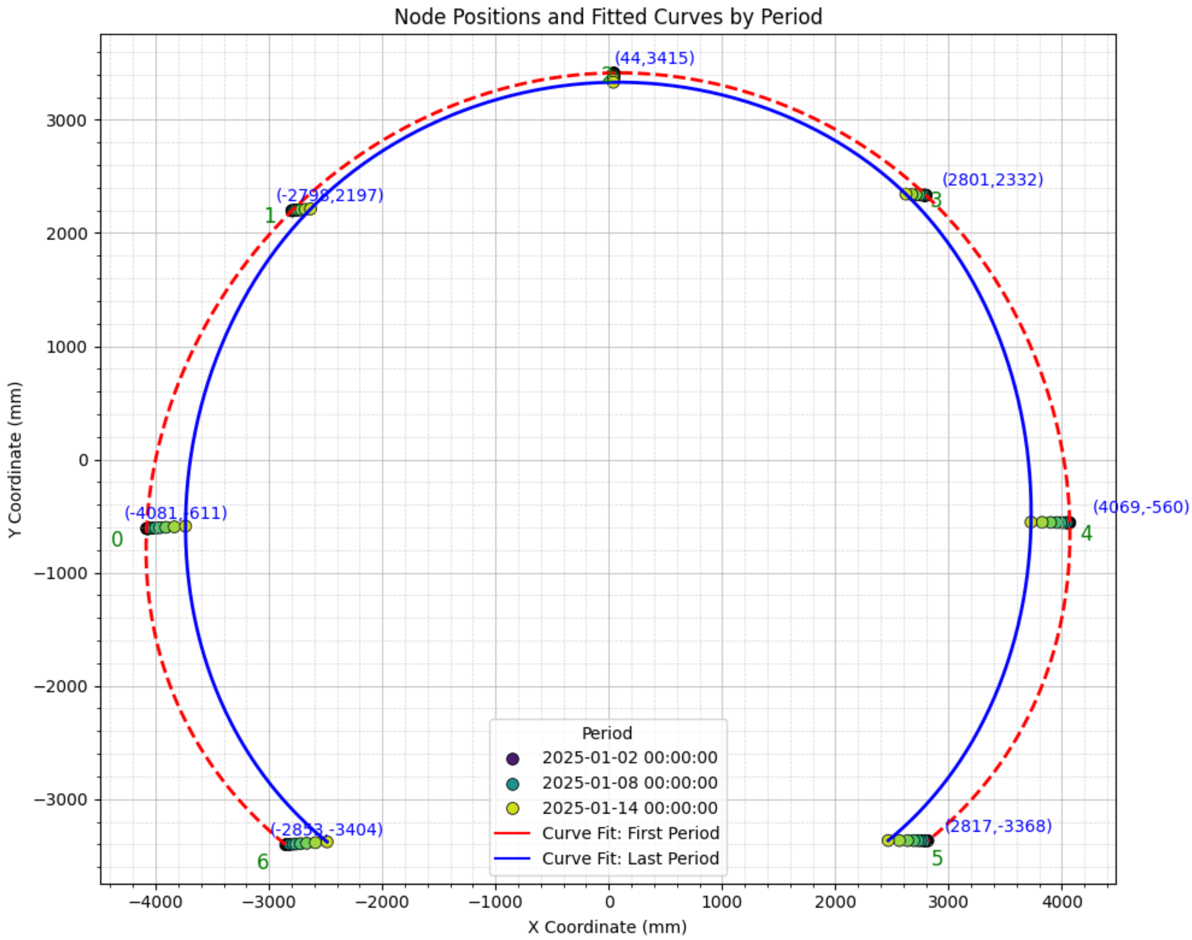

Figure 1 *The simulation of tunnel convergence by assigning all markers to moving in at increasing rate. The curve fitting on actual deformation was performed to extract the curvature and radial strain for analysis of tunnel closure.*

The convergence monitoring report often represent the movement in Horizontal and Vertical offset.

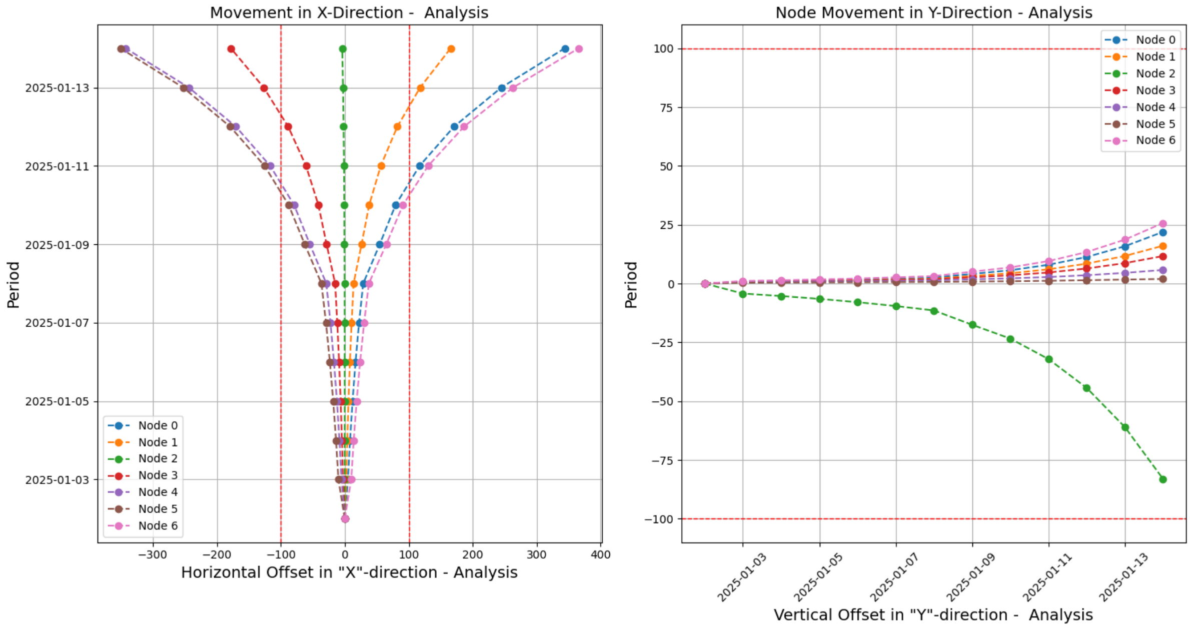

Figure 2 *The convergence report showing horizontal and vertical offset of each node is commonly used in convergence report by geodetic survey. This representation is simple and straight forward, but less meaningful to engineer when considering the design optimization.*

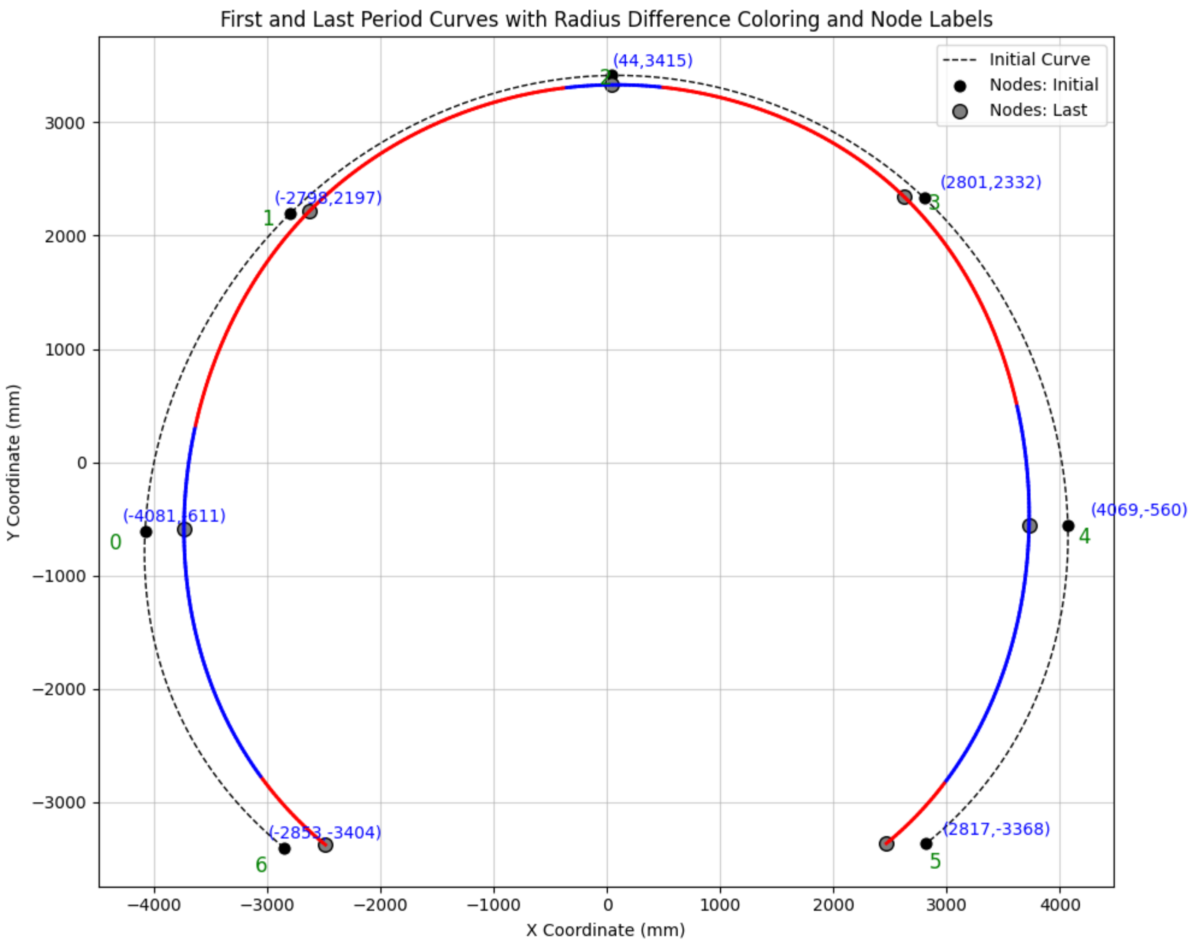

Figure 3 *Based on the strain data, and under the assumption that the tunnel support behaves as a thin section relative to the tunnel diameter, the radial strain distribution was calculated. The results indicate that regions shown in red exhibit negative radial strain, corresponding to compression, while regions shown in blue exhibit positive radial strain, corresponding to tension.*

The closure strain is calculated as the change in radius divided by the original radius of the curvature at the same location. A parametric curve generated from spatial data obtained from new approach using the formula below.

$$\frac{dr}{du} = r'(u) = (x'(u), y'(u), z'(u))$$

$$\frac{d^2r}{du^2} = r''(u) = (x''(u), y''(u), z''(u))$$

$$\frac{1}{R(u)} = \kappa(u) = \frac{\|r'(u)\, x\, r''(u)\|}{\|r'(u)\|^3}$$

$$\varepsilon_c\,(t) = \frac{R_0 - R_t}{R_0}$$

where:

κ is a curvature, measures how sharply the curve bends

R is a radius or the curve

ε_c *is a closure strain, measures relative contraction*

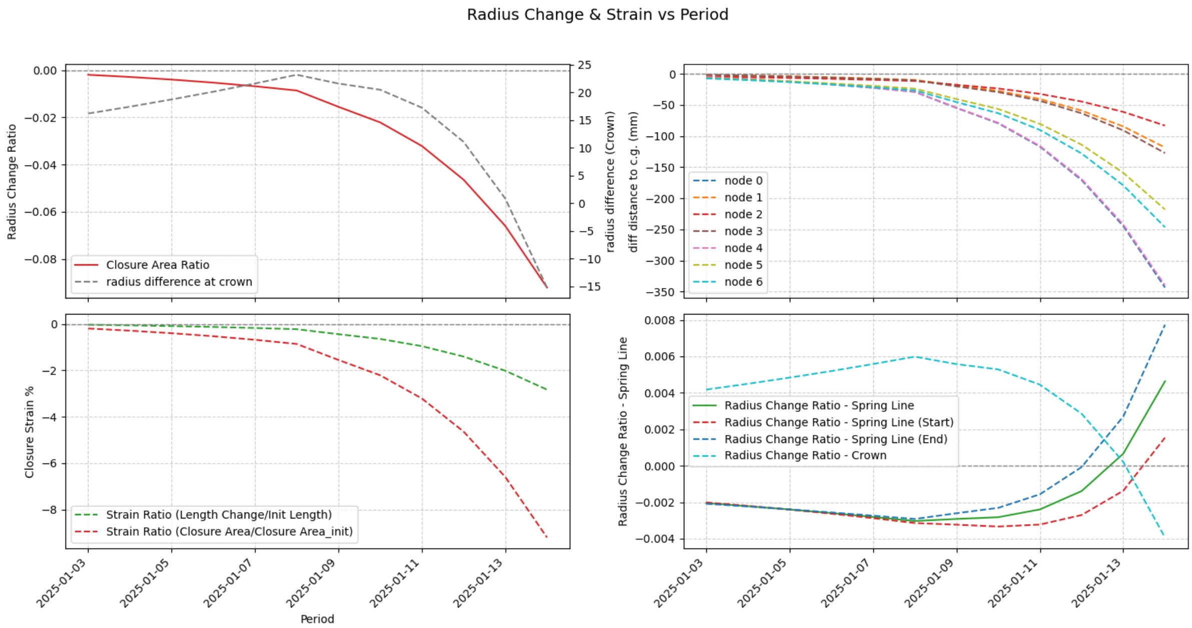

Figure 4 *The tunnel closure defined in this paper as radial strain which can be related to the previous works. The new representation of convergence data help engineer to review the risk of ground squeezing by comparing the measurement data to the design and provide mitigation measure if ground squeezing problem is prominent.*

Site Implementation

The Construction of the Mae-Ka Tunnel for the Den Chai-Chiang Rai-Chiang Khong Railway Project in the northern part of Thailand is one of the most challenging tunnel constructions as its underground condition is completely weathered rock and soil throughout the 2.7 kilometers.

The markers were installed at chainage 663+791, South Portal (up-track) as shown in ***Figure 5***. At the time of installation, ground squeezing had already commenced; however, the deformation

Figure 5 *The markers were installed after tunnel experienced ground squeezing.*

was still at an early stage. The convergence monitoring by geodetic survey plotted the trace of movement of target point as shown in ***Figure*** *7*.

The tunnel closure defined as radial displacement of tunnel normalized by its diameter, is generally used to quantify as closure strain. This parameter is closely related to the ratio of rock mass

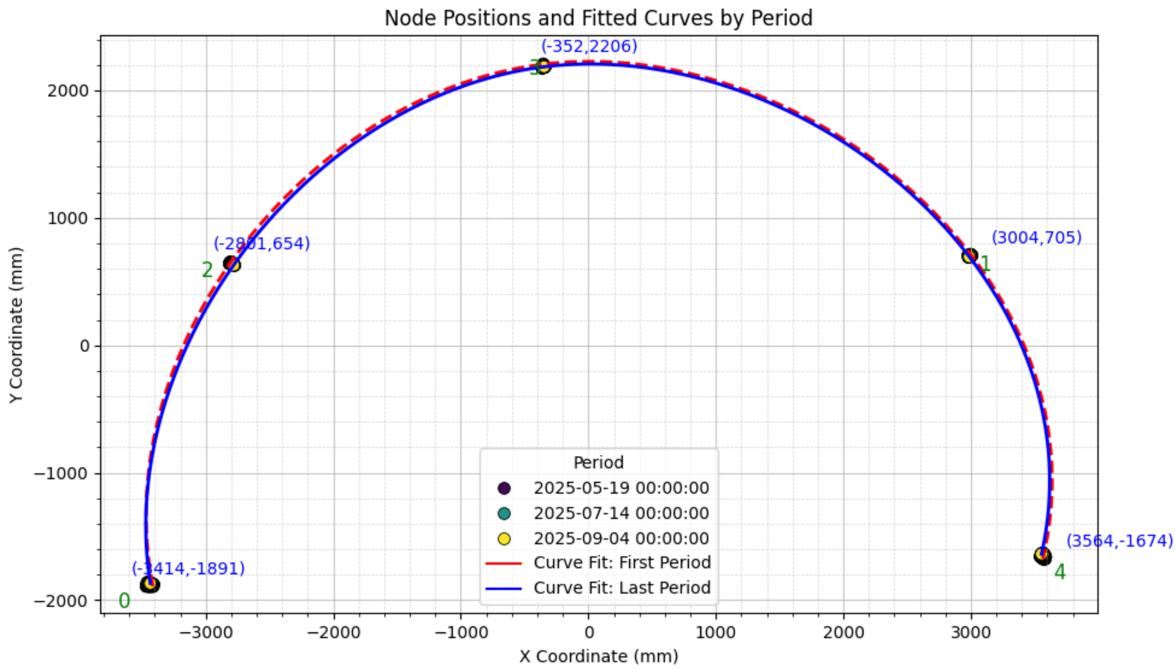

Figure 6 *The deformed shape was generated by fitting curves to the marker positions using the proposed method (computer vision). The displacement traces of the markers further revealed the progression of ground squeezing in this section.*

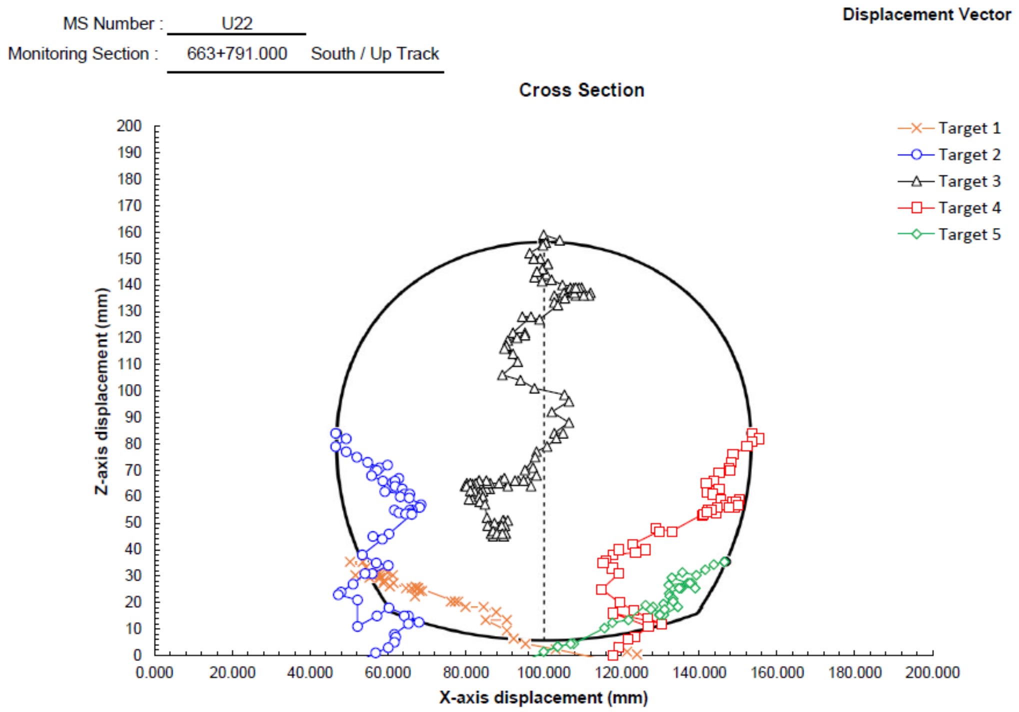

Figure 7 *The vector plot of target movements obtained from the geodetic survey indicates convergence, suggesting the presence of ground squeezing. However, this method provides limited insight into the severity of the squeezing, as it does not directly quantify the associated strain.*

strength to in situ stress, as described by (Hoek, 1998). In this paper, the closure strain (%) is defined as ratio of radius change to its original radius, which equivalent to circumferential strain.

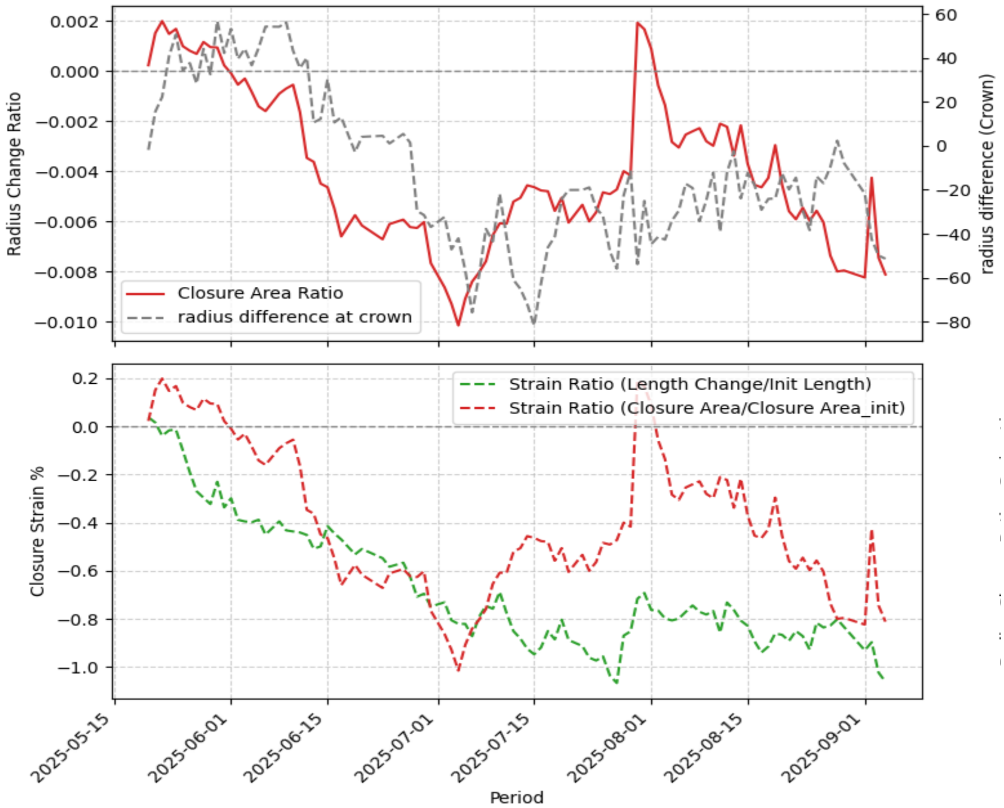

Figure 8 *(Top) The closure strain calculated by using ratio of change of radius to original radius at crown compared to the average closure by using closed area of initial and final state. (Bottom) the closure strain calculated by using ratio of change of circumferential length to original length of segment curve.*

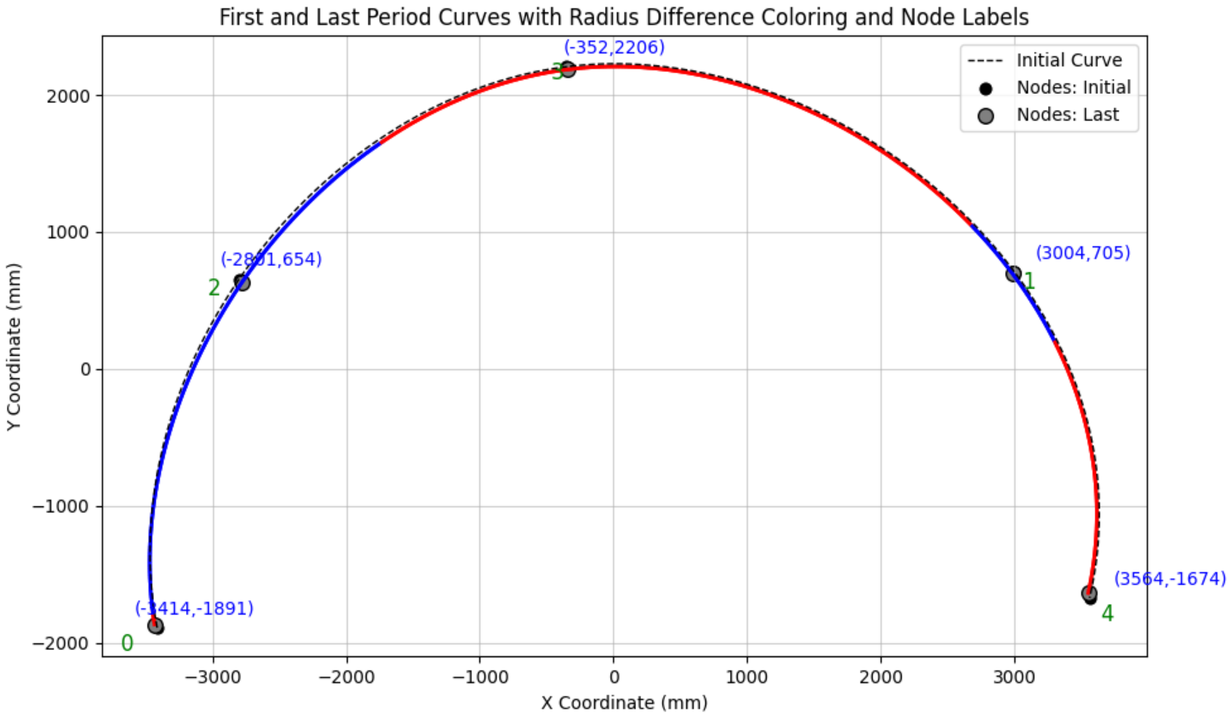

Figure 9 *A negative radial strain indicates compression along the tunnel segment curve, whereas a positive radial strain corresponds to tensile deformation.*

Conclusions

Conventional convergence monitoring using geodetic survey or mobile laser scanning (MLS) primarily records the displacement of markers. However, this information is often difficult for engineers to directly correlate with the load-bearing capacity of tunnel support systems, which is more fundamentally governed by strain. The displacements measured by geodetic survey and MLS represent a combination of overall translation and structural deformation; yet only the deformation component is directly related to the structural strength and stability. To address this, a new approach employing computer vision with fiducial markers and a novel point registration algorithm based on interconnecting pairwise distances is introduced. This method enables accurate alignment of target positions across time steps, thereby isolating deformation and allowing the estimation of strain within the tunnel support structure. Such information provides engineers with a more meaningful basis for evaluating whether the support system requires reinforcement, by directly comparing the measured strain under service conditions with its design capacity.

References

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