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ABSOLUTE DEFORMATION PROFILE MEASUREMENT IN TUNNELS USING RELATIVE CONVERGENCE MEASUREMENTS

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Abstract

Using convergence tape for measuring rock movement in a tunnel during construction to control the stability of the excavation is a common practice. In this technique a number of reference points (convergence pins) are installed around the tunnel periphery. After each face advance, the distance between pairs of pins is measured by 0.01 mm accuracy. Stability of the tunnel can then be evaluated according to the recorded deformations. Usually in this method, the exact locations of pins after deformations are not determined and just changes in length are measured. In this paper, methods of calculating exact coordinates of pins are presented by using convergence tape as the main instrument and leveling tools and single point extensometers as complementary. Recommendations are also made to optimize the installation location of the pins to maximize obtained information from the readings and ease of interpretations. In the second part of the paper, error sources in Sakurai's formula for back analysis of tunnel deformation is detected and eliminated by using the offered generalized formula.

1. Introduction

Instrumentation of excavations during and after construction is the best method for monitoring the stability of underground structures. Many different types of instrument are available for this purpose such as tape and rod extensometers, load cell and pressure cell *etc*. Tape extensometer is the most common type of instrument for displacement measurement of rock mass around tunnel periphery. This is a relatively inexpensive portable tool and very easy to use. Many researchers, such as Sakurai (1981) and Hisatake (1999) have proposed methods of stability assessment for tunnels based on convergence measuring results. The general practice with tape extensometer is to obtain relative displacement of tunnel periphery and asses the stability based on the slope of displacement – time graph. If rock movement accelerates with time, it can be a case of instability otherwise the tunnel is stable. In this type of analysis, the absolute displacement of each pin is not calculated but instead relative change in length between a pair of pins is determined. If one can determine the absolute displacement of each pin around tunnel, it can provide valuable information for further analysis.

This paper is focused on methods which make possible the determination of absolute displacement of pins during convergence measurement with assistance of some peripheral accessories which are usually available at site. Special arrangements for pins are also proposed which can facilitate determination of the aforementioned parameters with minimizing any interference with other activities.

2. Problem definition

Determination of exact location of pins in space is required for most back analysis methods. This can theoretically be done by surveying tools. Problems associated with this approach are limited accuracy of the typical tools, existence of dust and limited access to the points in the roof. The main aim in here is to make use of the accurate measurements that usually take place for stability purposes by tapes and to eliminate the need for using surveying tools for locating the pins.

The main problem in obtaining absolute displacement of pins in convergence operations is due to the fact that the number of unknowns is more than the number of equations in analytical approach. In figure 1 for example, 5 pins are installed around the tunnel. To determine the exact location of each pin, 2 parameters (x and y coordinates) must be defined therefore 10 parameters altogether are unknown. In this example 10 diameters can be measured using convergence tape but these sets of equations can still not be solved since the determinant of coefficient matrix is zero. Practically, this means that convergence measurements can only give relative displacements not absolute ones. To overcome this problem, graphical and analytical methods are proposed as follows.

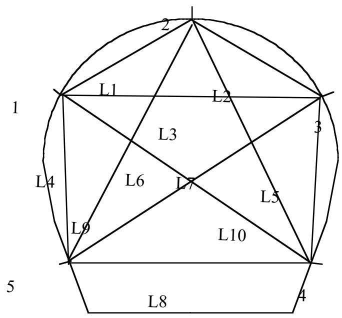


Figure 1: Possible diagonal readings with 5 pins.

3. Graphical method

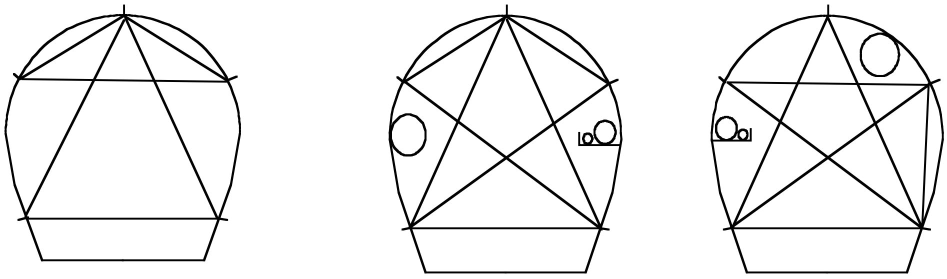
To determine the exact coordinates of pins after deformation of tunnel, one of the pins is assumed as reference point (*i.e.* pin 5 then $x_5,y_5=0,0$). It is also assumed that the diagonal between pins 5 and 4 is horizontal (meaning $y_5=y_4$). By these assumptions, three unknowns are omitted and 7 remains to be determined. It will be seen that using 7 diagonals are enough to determine the exact coordinates of the points. The arrangement of these 7 diagonals among 10 possibilities is a delicate choice. In figure 2 a non proper arrangement (case a) and two suitable arrangements (cases b and c) are shown for comparison. The first arrangement for diagonal readings prevents application of this graphical method, but the other two will facilitate this approach. Other facilities in the tunnel also exist, such as air and water pipelines or electricity cables that determine which arrangement case (b or c) is the most suitable one with minimum interference with other operations.

The first step after deciding on the most suitable pin arrangement is to find their initial locations (before tunnel convergence) in space by diagonal measurements initially performed by convergence tape. According to figure 3, the steps for finding the location of pins are summarized as follows.

Step 1- Draw a horizontal line with length L7 (between pins 5 and 4)

Step 2- Then from pin 5 draw a circle with radius L5 (the location of pin 3 is somewhere on this circle). The same should be done from pin 5 but with radius L3 for pin number 2.

Step 3- From pin 4 draw a circle with radius L4 to cross the loci of pin 2. At this point the location of pin 2 is determined.



(a) (b) (c)

Figure 2: Non-suitable arrangement (a), suitable arrangements based on the location of facilities (b and c).

Step 4- From point 2 draw a circle with radius L2 to cross the loci of pin 3 and find the location of this pin.

Step 5-From pin 4 draw another circle with radius L6 and find the location of pin 1 using the diagonal L1 from pin 2 the same way it was performed for pin 3.

At this stage the exact location of all pins at installation time (zero time) is determined. It is notable that in this method the only measuring tool used was tape extensometer and no surveying instruments were required (apart from the fact that for installation of diagonal L7 horizontally, one might use a leveling tool). The whole steps can be done using a simple graphical tool such as ACAD program. This can also be performed using analytical solutions by crossing two circles with known radii (i.e. L3 and L4) and known center points (pins 5 and pin4 respectively) to find the coordinates the other pins.

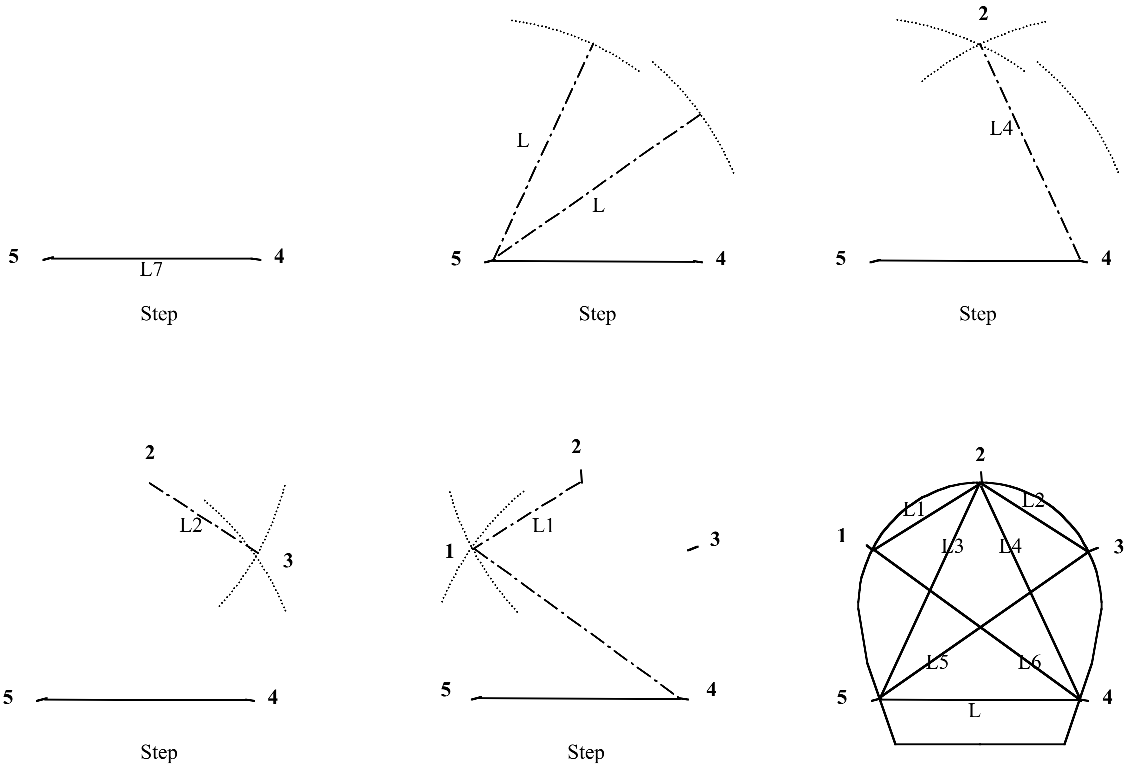
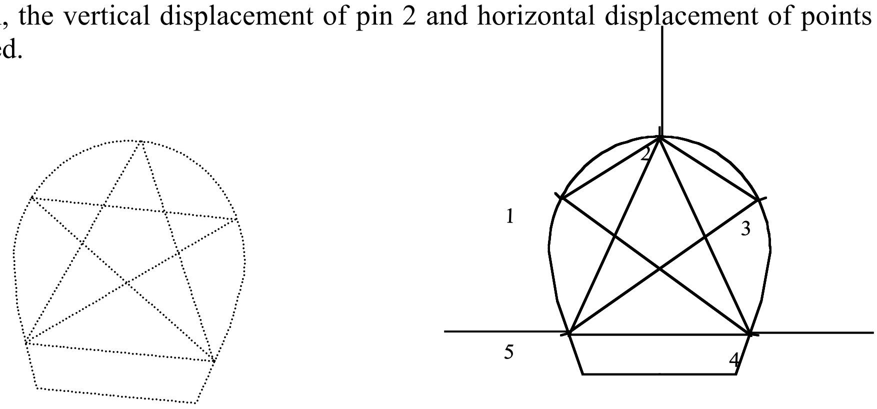


Figure 3: Steps for finding the coordinates of pins in graphical method.

During gradual advance of the tunnel face, the convergence measurements are performed progressively. When the face is far enough from the convergence station so that no further advance can affect rock movement, the displacement – time graphs will level off and displacements reach a constant magnitude. At this stage we can proceed with determination of new pin locations. The sequence for this part is exactly the same as one described before but this time the new diagonal lengths are employed. Once this is done, the deformed shape of the tunnel is determined (figure 4a). It is clear that this new shape might be displaced from its initial location and rotated as well. To determine the exact location and direction of the new deformed shape of the tunnel, the followings needed to be done;

Step 1- Before any advance in tunnel excavation, install long enough rebars which are anchored to the rock at their end point (debonded elsewhere) at points 5, 2 and 4 according to figure 4. Rebars are long enough to guarantee no rock movement at the end points. In this configuration, the vertical displacement of pin 2 and horizontal displacement of points 4 and 5 are determined.

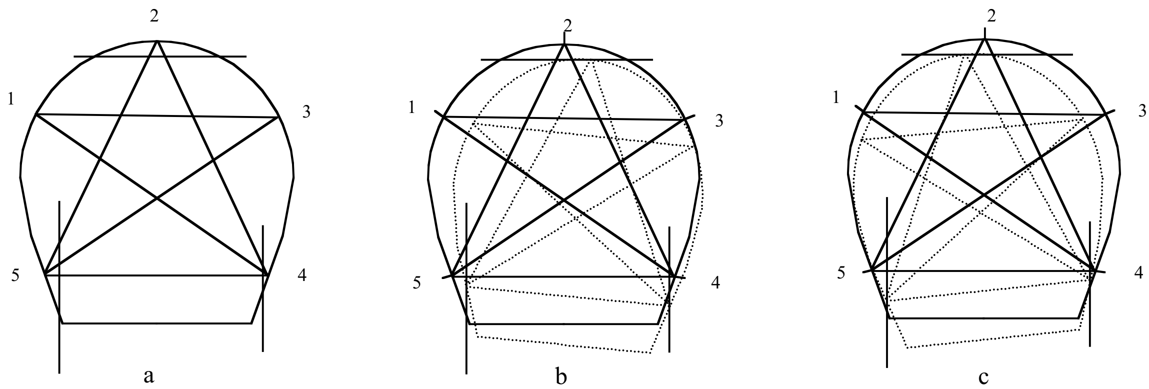


a b

Figure 4: Finding deformed profile (a) and measurement of total tunnel displacement at three points (b).

Step 2- on the original configuration of pins, three lines (two vertical lines close to the pins 4 and 5 and one horizontal line close to pin 2, with the distance measured from the rebar movements) are drawn (figure 5a). The new location of pins 2, 4, 5 should be somewhere on these three lines.

Step 3- Drag and rotate the deformed configuration of pins so that pins 2, 4 and 5 lie on these three lines. At this stage there are usually two solutions available based on the rotation direction of the deformed grid (figures 5b and 5c). The final solution between these two possibilities is decided based on the direction of diagonal L7 (whether this is inclined to the right or left). Now the exact location of the pins in the space after deformation of tunnel is determined and exact coordinates of each pin is now measured easily from the graphical program.



a b c

Figure 5: Finding the final shape of the deformed profile graphically.

4. Analytical approach

As Sakurai (1981) has discussed, if the initial location of two pins (with coordinates of (u_1,v_1) and (u_2,v_2)) with length (L) is change to a new position (u'_1,v'_1) and (u'_2,v'_2), the length change (Δl) can be written as:

$$(\Delta u_2 - \Delta u_1)Cos\theta + (\Delta v_2 - \Delta v_1)Sin\theta = \Delta l \tag{1}$$

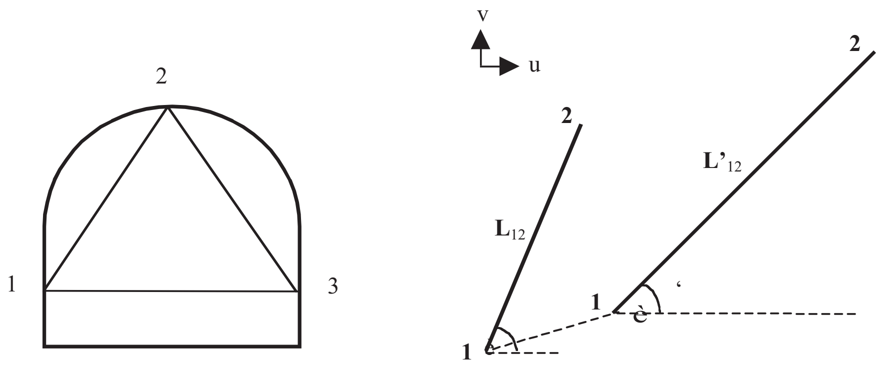


Figure 6: Length change after moving two points of a diagonal.

To simplify the discussion, we limit the analysis to a three pin situation with three diagonals of reading. There are some simplifying assumptions inherent in this equation which can be sources of error if one is not aware of those. These assumptions are:

- The displacements of the pins are small.
- Rotation of the diagonals during deformation is negligible
- The vertical displacements of points 1 and 3 are neglected.
- The horizontal displacement of points 1 and 3 are known.
- Diagonal 1-3 is assumed horizontal.

To eliminate some of these limitations, especially the rotation component, we proceed as follows:
If the diagonal L_{12} (between pins 1 and 2) is moved and rotated in space (figure 6), the original and new coordinates of the pin 1 can be written as:

$$u_1 = L_{12} Cos\theta \qquad v_1 = L_{12} Sin\theta \tag{4}$$

New coordinates after relocation are

$$u'_1 = L'_{12} Cos\theta' + \Delta u_2 \qquad v'_1 = L'_{12} Sin\theta' + \Delta v_2 \tag{5}$$

The displacements of each point can then be written as

$$\Delta u_1 = u'_1 - u_1 \qquad \Delta v_1 = v'_1 - v_1 \tag{6}$$

Replacing (4) and (5) in equation (6) yields

$$\Delta u_1 = L'_{12} Cos\theta' + \Delta u_2 - L_{12} Cos\theta \tag{7}$$

$$\Delta v_1 = L'_{12} Sin\theta' + \Delta v_2 - L_{12} Sin\theta \tag{8}$$

or

$$\Delta u_2 - \Delta u_1 = L_{12} Cos\theta - L'_{12} Cos\theta' \tag{9}$$

$$\Delta v_2 - \Delta v_1 = L_{12} Sin\theta - L'_{12} Sin\theta' \tag{10}$$

If the two sides of equation (9) is multiplied by *Cos t* and equation (10) by *Sin t*, we have

$$(\Delta u_2 - \Delta u_1)Cos\theta = L_{12}(Cos\theta)^2 - L'_{12} Cos\theta' Cos\theta \tag{11}$$

$$(\Delta v_2 - \Delta v_1)Sin\theta = L_{12}(Sin\theta)^2 - L'_{12} Sin\theta' Sin\theta \tag{12}$$

Adding two sides of equations (11) and (12) returns

$$(\Delta u_2 - \Delta u_1)Cos\theta + (\Delta v_2 - \Delta v_1)Sin\theta = L_{12} - L'_{12}Cos(\theta - \theta') \tag{13}$$

Comparing equations (13) and (1) shows that in Sakurai's assumption, the rotation effect is neglected and if we assume $\theta = \theta'$ then equation (13) turns into equation (1).

Having extended the Sakurai's equation, we can now proceed with our analytical solution to find the exact locations of the deformed pins in a 2D space with three diagonals. In this approach, we require to know

- The angle of one diagonal with horizontal line before and after movement (or assuming this diagonal to be horizontal) as discussed in graphical method previously.
- Assume coordinates of a pin as reference point and determine the new coordinates after movement (for example using long rebars).

For point 1' we can write -

$$L'^2_{21} = (u'_1 - u'_2)^2 + (v'_1 - v'_2)^2 \tag{14}$$

In equation (14), points (u'_1, v'_1) and (u'_2, v'_2) are coordinates of points 1 and 2 after deformation. We also have

$$\Delta v_1 = v'_1 - v_1 \qquad \Delta u_1 = u'_1 - u_1 \tag{15}$$

in which u_1 and v_1 are known parameters. Combining equations (14) and (15) and using equation (13), a system of two equations with two unknowns is formed from which the coordinates u'_1 and v'_1 can be determined. This would yield two sets of answers which mean that the new diagonal can either be rotated positive or negative with respect to the original diagonal direction. The same as graphical method, the real answer can be judged based on the inclination of the new diagonal with respect to its original direction.

4. Conclusions

Due to the wide spread use of convergence tape in monitoring tunnel stability it is important to try and get as much information as possible from this simple operation. Methods are proposed in here enabling calculation of exact location of pins due to tunnel advance based on convergence tape measurements and simple leveling tools. Knowing exact location of pins in tunnel can provide valuable information which is required for a proper back analysis operation. In this research the source of limitation inherent in Sakurai's equation is pin pointed and eliminated. The simplified assumption in that equation is not too important in rigid rock masses in which the deformations are small, but for softer or less intact rock masses these errors will rise and can affect the correctness and accuracy of our analysis. The proposed method has overcome this shortcoming.

References

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