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Measurement Methods for Cross-Sections of Tunnels Using Reflectorless Total Stations

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Abstract

Owing to the technical and economic aspects of the project management, pre-estimating the volumes of excavating, shotcreting, and concreting operations have been of great importance for the underground construction industry, especially in metro and highway tunnels. In this respect, we offer a reliable method based on the trigonometric geometry for estimating the required parameters of the conventional tunnels that are manually excavated via explosions and road-header machines. To this end, a geodetic network consisting of dense benchmarks are firstly realized outside the trench and throughout the excavated tunnel. The cross-sections of the tunnel are then mapped in the coordinate frame attached to the reference lines after orienting the reflectorless total station with respect to the geodetic network points and the predesigned reference lines. Consequently, by comparing the resultant coordinates of each cross-section at the excavating, shotcreting, and concreting stages, one can arrive at accurate estimation of the corresponding thickness, areas and volumes during different phases of the tunnel construction. The performance of the proposed method has been evaluated as a function of the central angles between the consecutive points on the arc of tunnel cross-section via a simulated dataset from an assumed D-shape tunnel. The numerical results have indicated that in the case of the consecutive central angle of 25 deg the estimated thickness, area, and volume errors are about 0.0057 m, 0.199 m^2, and 0.399 m^3, which can be considered as a clear indication of the reliability and applicability of the presented method.

Keywords: Cross-section mapping; Manual excavation; Conventional tunneling; Reflectorless total station; Concreting volume; Lining.

1. Introduction

These days, on-time construction and delivery of tunnels along with considering their cost-benefit aspects are of particular importance to the project management (Zhai, 2016). To this end, surveying engineering can play a crucial role in tunneling from the initial to end stages of the construction operations, i.e. staking-out, excavation directing, complementary measurements, design control, primary lining, and volume and thickness computations of shotcrete, so as to provide us with complying demanded criteria of the underground constructions (Ardalan et al., 2016). More specifically, the surveying methods can be employed to control the excavation operations through the extraction of the cross-sections and aligning the tunnels at the consecutive steps of the undergoing project (Su et al., 2006). In general, the current surveying methods can be classified into the three following categories (Gikas, 2012). (i) Close-range photogrammetric techniques to provide three-dimensional model using stereoscopic vision of pair or multiple images (Nakai et al., 2005), which has less been employed due to the environmentally poor-light conditions in the tunnels (Gikas and Daskalakis, 2008). (ii) In contrast to this technique, laser scanning methods can be utilized to collect a relatively noticeable volume of data in tunnels even with no light (Vezočnik et al., 2009); however, they may suffer from some practical restrictions relating to the high-cost and long-time implementations, besides possible constraints facing with managing the huge point clouds (Cheng et al., 2016; Puente et al., 2016). In particular, the error analysis of applying these methods was presented by Liu and Pan (2013), in which the contributing effects of a variety of degradation sources such as the ranger, scanner goniometer, environmental impact and data processing has been considered. (iii) The conventional manners can also be used to take some discrete measurements via the common surveying instruments, with the consequence deficiency in continuously

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three-dimensional illustration of the tunnels (Han et al., 2013). In the latter methods, mostly and usually, the cross-sections of tunnels are mapped just before and after the lining and shotcreting operations by means of reflectorless total stations (Xu and Wang, 2016). Consequently, comparing the mapped discrete points before and after the mentioned operations, one can achieve useful information about the thickness, areas and volumes of the excavated tunnels.

The main aim of the present contribution is to offer an effective method for estimating the main parameters of inspecting tunnels that are manually excavated through explosions and road-header machines. To do so, a dense geodetic network consisting of a number of benchmarks is firstly established throughout the tunnel, while the cross-sections are mapped in a coordinate frame that is attached to the reference lines. The reflectorless total station must be then oriented with respect to the realized geodetic network and the predesigned reference lines. Next, the cross-sections with constant meterage are mapped at each construction stage via the corresponding measuring points. At this step, the resultant coordinates of each section at the excavating, shotcreting, and concreting stages are compared with each other, and as such, we can arrive at estimating the corresponding thickness, areas and volumes for the tunnel of interest.

In the next section, the details of the proposed method to provide cross-section extraction of the tunnels are explained. The numerical results of the performance assessment of the proposed method via a simulated dataset of a D-shape tunnel are given in the subsequent section, while the errors in the estimation of the thickness, area and volume are evaluated as the number of the measuring points on the cross-section is increased. The last section is dedicated to the conclusion and final remarks.

2. Method

In the initial phases of designing the tunnel, the centerlines and the corresponding perpendicular cross-sections must be characterized on the plan maps. Indeed, the centerlines of the tunnel encompasses the reference lines, including the starting and ending points, which have been defined at the center and the lowest parts of each cross-section. These predefined reference lines are considered as the basis of all the tunnel construction operations, from staking out the cross-sections at the excavation stage to the frame-fixing and concreting phases. In the process of tunneling operations, we should first make a geodetic control network comprising of a various number of benchmarks established throughout the tunnel as proceeding with the excavation advancements, which the geodetic coordinates have been determined via traverse observations. The reflectorless total station in the field must then be oriented along with the coordinate system realized by this geodetic network, and consequently, the reference lines are appropriately introduced. In this way, we can stake out cross-sections relating to each reference line using the meterage and offset (i.e. the longitudinal and traverse distances) and elevations of the associating planning points, with respect to the starting point of the reference lines (Figure 1). It is worth-mentioning that at this stage we resort to the reference lines to direct the overall route of the tunnel excavation as similar as possible to the designed plan. However, due to the practical difficulties as well as the possible degradation of the instrumental accuracy, the excavated tunnels may not be exactly similar to the desired directions on the plan, and as such, it is required to survey some measuring points that are located on the cross-sections with certain distances from the starting point of the reference lines.

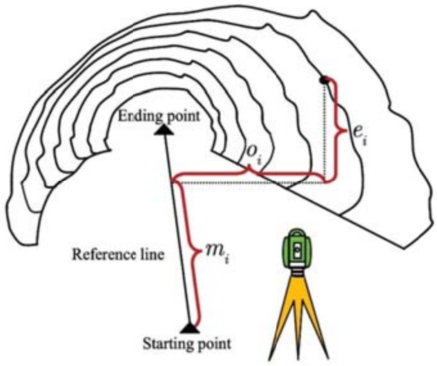


Figure 1. Schematic illustration of the procedure to determine the coordinates of measuring point i in the reference line-attached frame, with the offset (o_i), meterage (m_i), and elevation (e_i).

At this point, the shotcrete operations are performed in order to strengthen the initial configuration of the excavated tunnels; and therefore, the cross-sections must be mapped again to monitor the current layer of the constructed tunnel as compared with those of the former situations. Accordingly, the thicknesses, areas and volumes of the shotcrete layers can be achievable through comparing the mapping points on the cross-sections that have been measured just before and after the shotcrete operations. As the points are measured in the frame attached to the geodetic network, we must transform the resultant coordinates into the corresponding coordinates (meterage, offset and elevation) in the designing frame attached to the reference lines to control the excavation operations. Accordingly, if the reference line consists of the starting and ending points, namely points 1 and 2, one can arrive at the meterage of measuring point i with respect to the point 1 in the attached coordinate frame by the following trigonometric relation:

$$m_i = \frac{(\ell^2_{1i} + \ell^2_{12}) - \ell^2_{2i}}{2\,\ell_{12}} \tag{1}$$

where $\{\ell_{1i},\ \ell_{2i}\}$ are the distances of the measuring point i from points 1 and 2, while ℓ_{12} is distance between the points 1 and 2. Next, in order to derive the offset, we should consider an imaginary point 3 at the same elevation with the point 1, so that the baseline ℓ_{13} between points 1 and 3 would be perpendicular to the reference line. As a result, the coordinates of point 3 in the coordinate system attached to the geodetic network can be estimated through:

$$\begin{cases} X_3 = X_1 + \ell_{13}\sin(g_{13}) \\ Y_3 = Y_1 + \ell_{13}\cos(g_{13}) \\ Z_3 = Z_1 \end{cases} \tag{2}$$

where $\{X_1,\ Y_1$, and $Z_1\}$ are the coordinates of point 1 in the geodetic network frame, ℓ_{13} is an arbitrary value, e.g. the width of the tunnel, and g_{13} is the gisement angle of the baseline ℓ_{13} that can be obtained from:

$$g_{13} = \tan^{-1}\left(\frac{\Delta X_{12}}{\Delta Y_{12}}\right) + \frac{\pi}{2} \tag{3}$$

where $\{\Delta X_{12},\ \Delta Y_{12}\}$ are the relative coordinates of the baseline ℓ_{12}; and as such, the offset of the measuring point i can be expressed by:

$$o_i = \frac{(\ell^2_{1i} + \ell^2_{13}) - \ell^2_{3i}}{2\,\ell_{13}} \tag{4}$$

where ℓ_{3i} is the distance between point 3 and the measuring point i. Finally, one can arrive at the elevation of the measuring point i from the reference line-attached coordinate system:

$$\begin{cases} e_i = \sqrt{\ell^2_{1i} - (m_i^{\,2} + o_i^{\,2})} & if\ Z_i \geq Z_1 \\ e_i = -\sqrt{\ell^2_{1i} - (m_i^{\,2} + o_i^{\,2})} & if\ Z_i < Z_1 \end{cases} \tag{5}$$

where Z_i is the vertical coordinate of the point i. Having derived the resultant coordinates of the measuring points on the cross-sections just before $\{o_i,\ e_i\}$ and after $\{o'_i,\ e'_i\}$ lining or shotcreting operations, the area (a_j) of the lining/shotcrete layer at the cross-section j can be estimated by:

$$a_j = \frac{1}{2}\{(o_1e_2 + o_2e'_3 + \ldots + o'_ne_1) - (e_1o_2 + e_2o'_3 + \ldots + e'_no_1)\} \tag{6}$$

Having derived the areas of the cross-sections, the thickness of the cross-section j can be computed by:

$$t_j = \frac{a_j}{(\ell_j + \ell'_j)/2} \tag{7}$$

where ℓ_j and ℓ'_j are the summation of the surveyed lengths before and after the shotcreting/lining operations along the cross-section that can be derived by:

$$\ell_j = \sum_{i=1}^{n} \sqrt{(o_{i+1} - o_i)^2 + (e_{i+1} - e_i)^2} \quad (8)$$

$$\ell'_j = \sum_{i=1}^{n} \sqrt{(o'_{i+1} - o'_i)^2 + (e'_{i+1} - e'_i)^2} \quad (9)$$

As schematically shown in Figure 2, the volume $v_{j,j-1}$ of the shotcrete layer between the two consecutive cross-sections along with the tunnel centerline can also be resulted in:

$$v_{j,j-1} = \frac{1}{2}(a_{j-1} + a_j) \times d_{j,j-1} \quad (10)$$

where $d_{j,j-1}$ is the separation distance between the two consecutive cross-sections, while $\{a_{j-1}, a_j\}$ are the corresponding areas.

At this step, according to Figure 3, we can estimate the ultimate volume of concreting operations at each part, with length of 6 m as an example in the form of the hydraulic frame shown in Figure 4, via the following formula if their components are coordinated with respect to the reference lines system:

$$v_f = \frac{1}{2}(a_1 + a_2) \times d_{1,2} + \frac{1}{2}(a_2 + a_3) \times d_{2,3} + \cdots + \frac{1}{2}(a_{k-1} + a_k) \times d_{k-1,k} \quad (11)$$

where a_k is the area of the mapped section k in part f, and $d_{k-1,k}$ is the distance between the two consecutive mapped cross-sections. The final product is the total amount of concrete during the whole tunnel course, which can be considered for employers as an appropriate estimation of the approximate invoice.

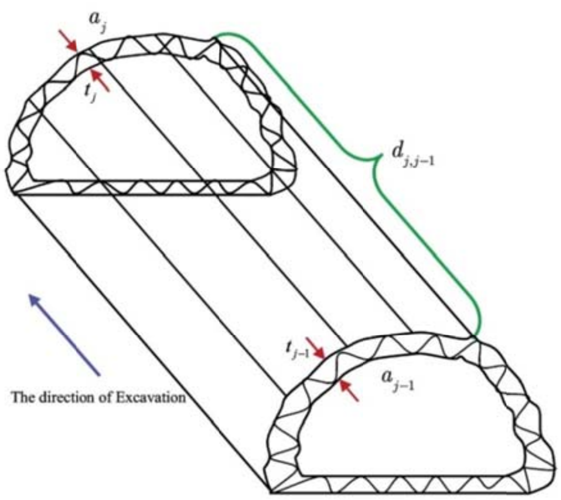


Figure 2. A schematic view of two consecutive cross-sections along with the tunnel direction.

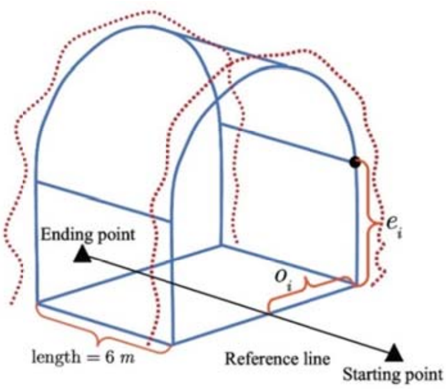
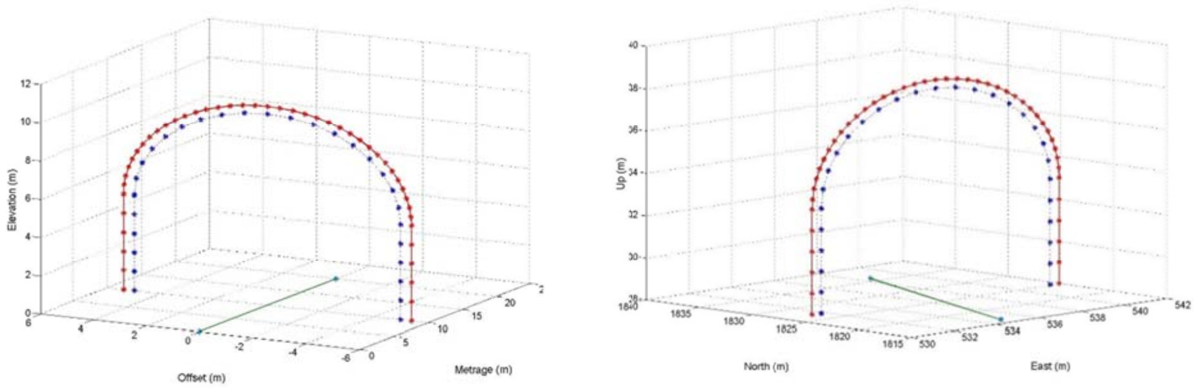


Figure 3. Schematic illustration of the hydraulic frame (solid lines), the surface of the shotcrete layer (dashed lines). Note that the components of the hydraulic frame can be specified via offset (o_i) and elevation (e_i).

Figure 4. A view of a hydraulic frame used for the tunnel construction.

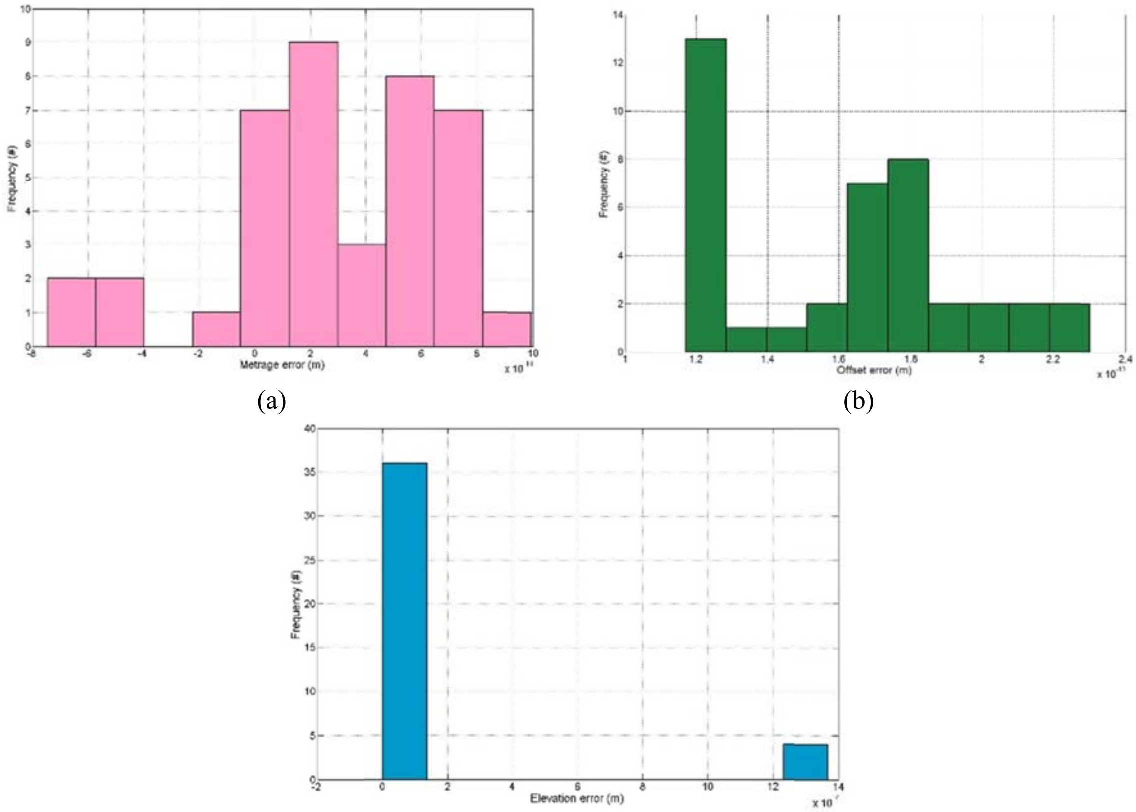
3. Results and discussions

In order to demonstrate the effectiveness of the method, the proposed method has been applied to a simulated dataset that has been considered for an assumed D-shaped tunnel with two similar cross-sections. To this end, we synthesize the coordinates of some measuring points on each cross-section in the reference line coordinate system before and after lining as shown in Figure 5a. The corresponding geodetic coordinates have then been derived from rotation of the synthetic coordinates around the third axis of the reference line frame, with magnitude of the gisement of the centerline including the starting and ending points 1 and 2 that are coordinated in an arbitrary traverse-based frame (Figure 5b). It should be noted that the areas and thicknesses of the cross-sections between before and after lining surfaces are to be 10.53 m^2 and 0.4 m, respectively. Additionally, with supposing the 2 m-separation of the two cross-sections, the volume is to be 21.07 m^3. Figure 6 shows the estimated errors of applying the method to the synthetic dataset in geodetic coordinate system, while the distance of the baseline perpendicular to the center line is assumed to be 5 m. According to the figures, the shown errors are negligible, which can be considered as a clear indication of the success of the method to estimate the reference line coordinates of the measuring points before and after the lining. Consequently, the resultant area of the cross-sections between the surfaces before and after the lining is about 10.34 m^2, while the corresponding volume is 20.67 m^3. Additionally, the lining thickness of 0.39 m has been estimated. With comparison of these estimated values with the associating benchmarks, we can infer that the area, volume and thickness errors are about 0.199 m^2, 0.399 m^3, and 0.006 m respectively. From the practical point of view, these ranges of errors can be insignificant, and as such, this is another sign of the efficiency of the presented method in order for budget management.



(a) (b)

Figure 5. Synthetic coordinates of the measuring points on the cross-sections in a) the reference line and b) geodetic coordinate systems before and after lining in solid and dashed lines, respectively.

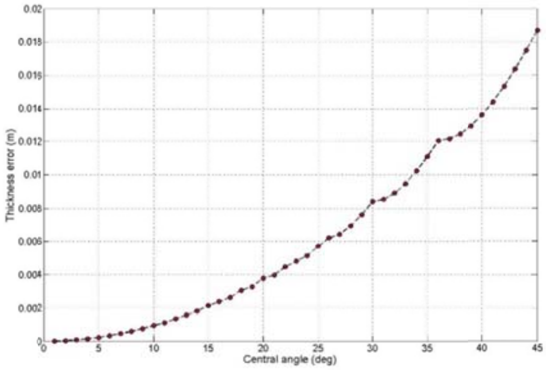


(a) (b)

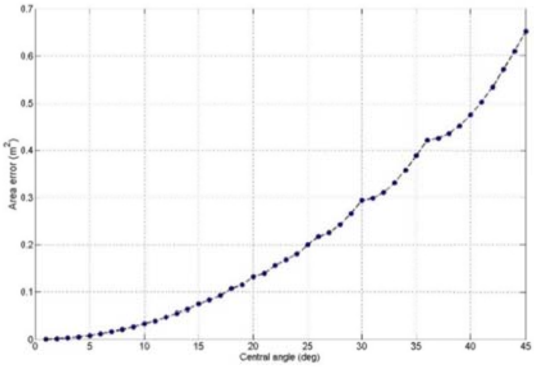
(c)

Figure 6. Estimated errors of the results of the application of the method to the geodetic coordinates of the cross-sections before and after lining, with respect to the simulated benchmarks. a) Meterage, b) offset and c) elevation errors.

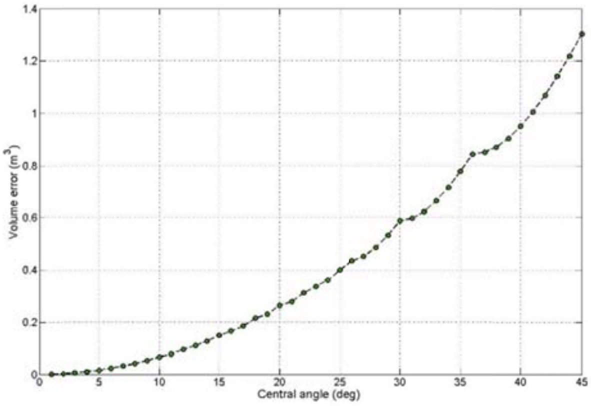
At this point, we are to investigate the effect of the distribution of the measuring points at the arc of the cross-section on the accuracy of the final products. To this end, the estimated errors in the thickness, area and volume computations were derived as a function of the central angle between the two consecutive measuring points, which the simulated ones have been considered as the references. The results are shown in Figure 7. According to the figure, the errors in the derivation of thickness, area and volume are gradually increased as the number of measuring points is decreased, such that in the case of nine measuring points on the arc (corresponding to the central angle of 20 deg between the two consecutive points if the arc to be a whole semicircle), we face with an errors of 0.004 m, 0.1319 m^2 and 0.2638 m^3 in thickness, area and volume estimation, respectively. This achievement can also be verified by the analytical assessment of the relative errors ($\frac{e}{R}=\frac{\widehat{L}-\bar{C}}{R}=\Delta-2\sin(\frac{\Delta}{2})$) due to the deviation between the chord ($\bar{C}$) and arc ($\widehat{L}$) lengths, in which Δ is the central angles of the arc. As can be seen in Figure 8, similar results can be perceiving and as such the relative errors in the estimation of the thickness, area and volume via the proposed method are raised as a function of the central angles between the two consecutive measuring points are getting wider. With comparison of Figures 7 and 8, one can deduce that the increasing rates of the errors can be negligible while the central angles between the consecutive points on the cross-section arc are within 15 deg. In general, the number of measuring points on the cross-sections must be pursued the employers viewpoint, considering the project operations time, budget and the intended accuracy in order of priority.



(a)



(b)



(c)

Figure 7. Errors in the estimation of the thickness, area and volume by the proposed method as a function of central angles between the two consecutive measuring points, with respect to the simulated references. a) Thickness, b) area and c) volume errors.

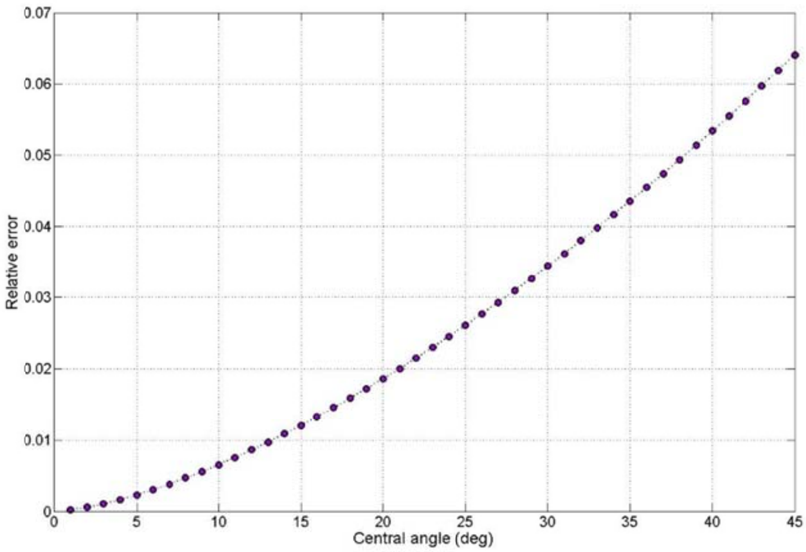


Figure 8. Relative errors in the estimation of the thickness, area and volume via the proposed method as a function of central angles between the two consecutive measuring points, with respect to the simulated benchmarks.

4. Conclusion and final remarks

An efficient method has been presented in order to attain the required parameters of the conventional tunnels that are manually excavated. Indeed, thanks to the relations in the trigonometric geometry, it is possible to derive the coordinates of the measuring points in the reference line attached frame from those in the geodetic coordinate system, and as such, the concreting consumptions can be controlled more precisely. The performance, efficiency and applicability of the presented method have been assessed via synthetic dataset. According to the simulation results, the errors in estimating the lining thicknesses, the cross-section areas and the volumes of the consecutive cross-sections can be estimated via an appropriate accuracy, thanks to the advantages of the proposed method.

As the practical point of views, it is a must to survey additional points on the cross-sections wherever the deformations including concave and convex features exist. The most accurate results can be achieved if the number of measuring points is increased, while the associating distribution is to be uniform. The coincidence points of the direct lines and the arc as well as the corner points on a cross-section must be measured; however, if this is not the case due to the environmental limitation, some imagination points must be considered in the computational procedure in return. In general, the measuring points must also be on the cross-section plane as far as it is feasible, while the acceptable deviation from the plane should be taken into account. Moreover, the most accurate control of the shortest distance between the two consecutive cross-sections, although the trade-off between the cost and the time of the project proceeding on the one hand and the accuracy of the final products on the other, must also be supposed. In order to mitigate the effects of the errors relating to the coordinates of the geodetic network points on the resultant parameters, it is advised that the same geodetic points are employed to orient the total station in the surveying operations just before and after the shotcreting and lining processes. We can overally recommend that the presented method can be used to provide employers with required information in the tunneling and underground surveying.

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