ASSESSMENT OF NON-LINEAR REGRESSION APPROACH FOR BACK-ANALYSIS ON TUNNELLING-INDUCED SURFACE SETTLEMENT– A CASE STUDY IN HO CHI MINH CITY

ĐÁNH GIÁ PHƯƠNG PHÁP HỒI QUY PHI TUYẾN TRONG PHÂN TÍCH ĐỘ LÚN MẶT ĐẤT GÂY RA BỞI THI CÔNG HẦM – NGHIÊN CỨU TRƯỜNG HỢP TẠI THÀNH PHỐ HỒ CHÍ MINH

Le Thanh Binh*, Nguyen Anh Tuan, Nguyen Trong Tam
Ho Chi Minh City University of Transport, Vietnam
[*]binh.le@ut.edu.vn

Abstract: *Previous researchers proved that surface settlement induced by tunnel constructions can be described by a Gaussian curve with the two key parameters K, the trough width factor, and V_L, the volume loss. Knowing K and V_L values enables surface settlement trough to be calculated which is essential to determine the potential effects of tunnelling to soil and surrounding buildings. A non-linear approach has been widely used to estimate K and V_L values from field measurement using the sum of absolute errors. However, the reliability of the determined results could not be quantified. This paper uses surface settlement data from a case study in a tunnelling project in Ho Chi Minh city to determine K and V_L using the non-linear regression approach. Then, a method was proposed to quantify the goodness of fit and the reliability of the determined K and V_L. The results show that knowing the reliability of the K and V_L is essential for the designers and researchers to determine if these values should be used as reference for their calculation in a similar tunnelling project to predict surface settlement.*

Keywords: *Tunnelling, case study, empirical method, field data, non - linear regression.*

Chỉ số phân loại: *2.4*

Tóm tắt: *Các nhà nghiên cứu trước đã chứng minh rằng độ lún mặt đất gây ra bởi việc thi công hầm có dạng đường cong Gaussian với hai thông số chính là K, trị số bề rộng, và V_L, thể tích mất mát đất. Từ K và V_L, đường cong lún có thể được tính toán để đánh giá các ảnh hưởng tiềm năng của việc thi công hầm đến đất và công trình lân cận. Phương pháp hồi quy phi tuyến được sử dụng rộng rãi để ước lượng giá trị K và V_L dựa vào số liệu hiện trường thông qua tổng sai số tuyệt đối. Tuy nhiên, độ tin cậy của các giá trị này không được định lượng. Bài báo này sử dụng số liệu hiện trường từ công trình thi công hầm tại thành phố Hồ Chí Minh để xác định giá trị K và V_L theo phương pháp hồi quy phi tuyến. Sau đó, một phương pháp bổ sung được đề xuất để định lượng độ chính xác và độ tin cậy của cặp giá trị K và V_L. Kết quả cho thấy việc biết được độ tin cậy của giá trị K và V_L là rất quan trọng cho đơn vị thiết kế và các nhà nghiên cứu trong việc lựa chọn các giá trị này khi tính toán và dự đoán độ lún của mặt đất gây ra bởi thi công hầm tương tự trong tương lai.*

Từ khóa: *Thi công hầm, phương pháp thực nghiệm, dữ liệu hiên trường, hồi quy phi tuyến*

Classification number: *2.4*

1. Introduction

1.1. The overview of tunnel construction

In many urban environments the available over ground space is no longer adequate to sustain construction of new transportation systems to serve the growing traffic and congestion. This has led to an increase in the number of tunnelling projects for services and mass transit systems. Following this inevitable trend, a total of nearly 100km of tunnels, as a part of the metro line systems, have been planned in Hanoi and Ho Chi Minh City [1 - 4]. Basically, tunnelling is to create space for underground services by removing soil and replacing it by tunnels. Mair et al [7] reported that there are several methods to excavate tunnels including sprayed concrete lining (or sometime referred as New Austrian Tunnelling Method, NATM) and tunnel boring machine (TBM).

Nowadays, TBM are often used due to its advantageous capabilities including fast construction, better controlled ground movement, safety for workers and surrounding structures, minimal disruption to structures and activities on the surface etc

([5]). The tunnel in the line number 1 Ben Thanh Suoi Tien, Ho Chi Minh city was constructed using an Earth Pressure Balance Tunnel Boring Machine (EPB TBM) as the method is suitable with the soil condition in the area.

1.2. Tunnel construction using EPB TBM

The key aspect of an EPB TBM is the provision of adequate support at the tunnel face during excavation to control soil displacement [8]. Typical features of an EPB TBM are depicted in figure 1 [8].

During tunnelling process, the cutter head (1), powered by motor (2), excavates the soil under the cover of the tunnel shield (3). The excavated soil passes through the cutter head then enters the pressurised chamber which is immediately behind the cutter head. The excavated soil in the chamber is then extracted through a screw conveyor (5) to the discharge outlet (7) that leads to the conveyor belt (9) where the soil is transported to the outside of the tunnel. The speed of soil extraction from the chamber can be adjusted, i.e. fast extraction of soil will lead to decrease of chamber pressure and vice versa, to achieve the desired pressure in the chamber to balance earth pressure at the tunnel face. After each excavation cycle, tunnel lining segments (8) are erected within the TBM tail skin (3). As the tail of the tunnel leaves the tunnel lining, pressurised grout is injected behind the segments to fill the void between the external side of the tunnel lining and the excavated ground [8]. The cycle of excavation, lining segment erection and grout injection repeats until the completion of the designed tunnel.

1.3. Ground loss in TBM tunnelling

In TBM tunnelling, during the excavation of soil and installation of tunnel lining, soil deformations occur because of the five main sources (Figure 2) which are corresponding to the consequential construction stages as described below [9]:

- *Face movement:* caused by changes in soil stress due to excavation and the application of face pressure, provided at the TBM front, to balance earth pressure at this location. If the face pressure is smaller than soil and water pressures, then the ground mass in front of the tunnel will move towards the tunnel face.

- *Over-excavation:* it is common that the TBM cutter is larger than the tunnel diameter which causes over-excavation. This creates a gap between the excavated soil and the tunnel shield which allows ground to move towards the tunnel vicinity before stage 4 takes place.

- *Shield tapering:* for the ease of moving the TBM forward, the front of the TBM is normally larger than its end.

- *Tail void closure:* before the erection of tunnel lining and injection of grout, soils behind the TBM tail tend to move into the tunnel vicinity. The key factors that affect this component of soil movements are: soil properties, volume and speed of grout injection to fill the void, the speed of excavation.

Lining deformation: earth and pore water pressures cause deformations in tunnel lining. This component depends on some key factors including soil properties, depth of tunnel, water table level, properties of tunnel lining.

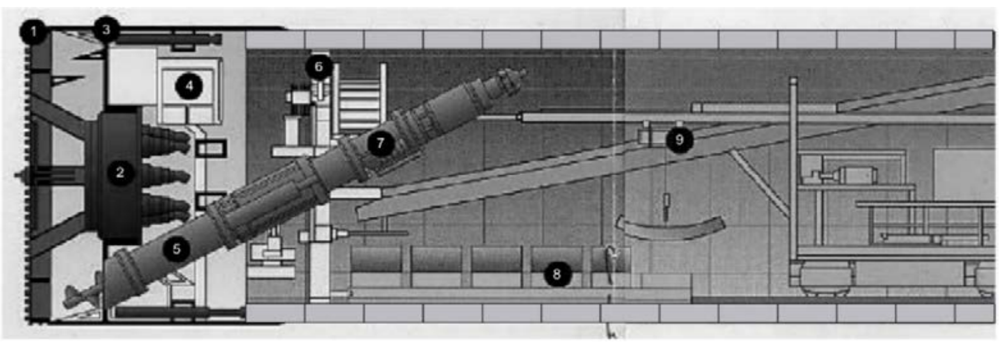


***Figure 1**. Earth Pressure Balance Tunnel Boring Machine (EPB TBM):*
1- Cutter head; 2 - Drive motor; 3 - TBM skin; 4 - Airlock; 5 - Screw conveyor; 6 - Lining erector arm; 7 - Soil discharge; 8 - Lining segments; 9 - Belt conveyor [8].

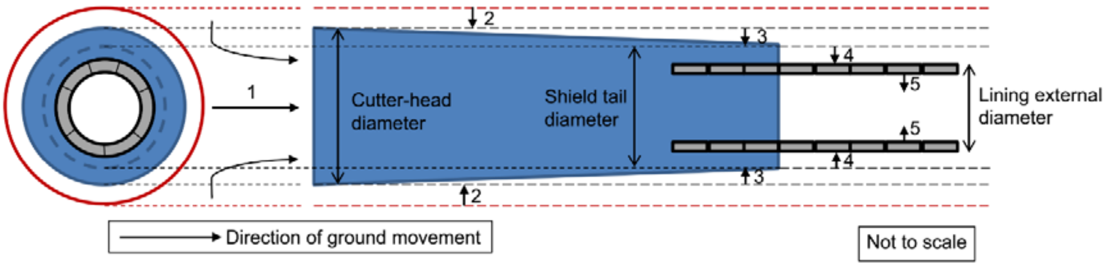


Figure 2. *Components of volume loss in TBM tunnelling [9].*

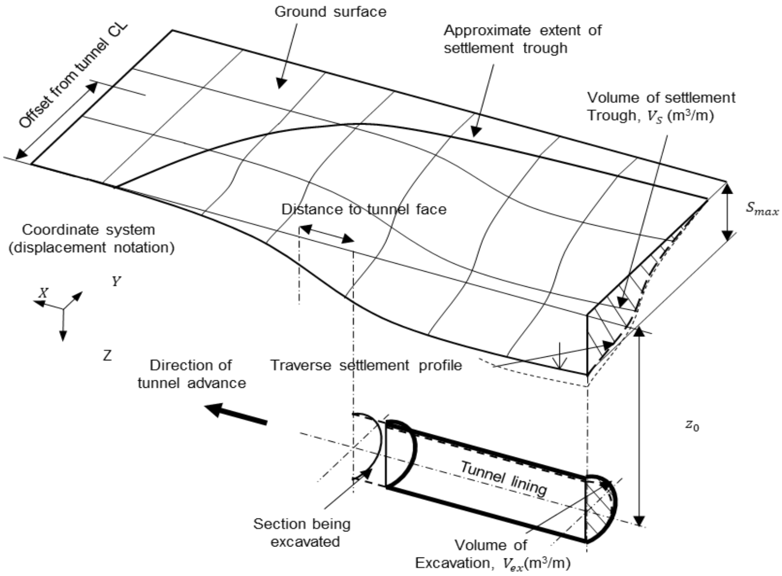


Figure 3. *Tunnelling-induced soil settlement (after [6]).*

The mentioned components caused soil deformations around the tunnel that results in settlement at the surface (Figure 3). These ground displacements may cause destructive damages to surrounding buildings. Therefore, predictions on the effects of tunnel construction to the deformations of soil and surrounding structures are very important to ensure the success of tunnelling projects.

2. Prediction of tunnelling-induced surface settlement

2.1. The shape of settlement trough

Previous researchers ([6], [7], [9], [10], [13], [14], [15]) demonstrated that the profile of tunnelling induced surface settlement has the shape of an inverse Gaussian curve (figure 4) and can be described by equation 1.

The parameters in Equations 1 are depicted in Figure 4.

$$S = S_{max} exp\left(\frac{-y^2}{2i^2}\right) \qquad (1)$$

Where:

S is surface settlement,

y is the distance from the tunnel centre line to the settlement point in the transverse direction;

S_{max} is the maximum settlement (usually corresponding to $y = 0$);

i is the distance from the centreline to the point of inflexion in transverse direction.

$$S_{max} = V_S/\sqrt{2\pi} i; \qquad (2)$$

$$V_S = V_L \times V_{exc}; \qquad (3)$$

$$V_{exc} = \pi \frac{D^2}{4}; \qquad (4)$$

$$i = K z_0 \qquad (5)$$

Where:

V_S is the magnitude of the settlement trough;

V_{exc} is the volume of excavation area;

V_L is the volume loss that indicates the ratio of V_S with V_{exc};

D is the excavation diameter.

Combining (2), (3), (4) and (5) gives:

$$S_{max} = 0.313 \frac{V_L D^2}{K z_0} \qquad (6)$$

Replacing Equations (5) and (6) to Equation (1), S can be calculated as;

$$S = 0.313\frac{V_L D^2}{Kz_0} exp\left(\frac{-y^2}{2(Kz_0)^2}\right) \quad (7)$$

In Equation 7, the tunnel diameter D and the tunnel depth z_0 are known and constant at a specific location. Therefore, the profile of the settlement curve, S, depends on the values of volume loss V_L and K. Discussion on these two values are presented in the following sections.

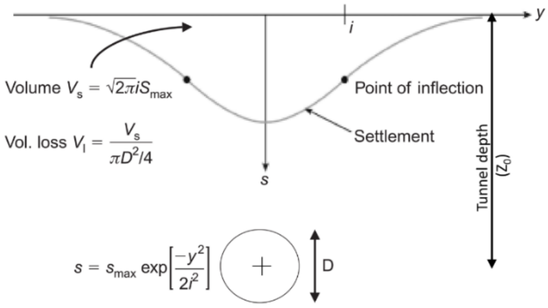


Figure 4. Usage of Gaussian curve to represent settlement trough [7].

2.2. Volume loss V_L

Volume loss V_L together with K govern the maximum soil settlement S_{max} (Equation 6). Volume loss V_L depends on many factors including soil conditions, tunnelling technique, tunnel geometry and quality of workmanship hence it is difficult to estimate V_L. A common approach to predict V_L is to use field data from case studies of similar projects and engineering judgement.

2.3. Settlement trough width parameter K

The width of the settlement trough is dictated by the value $i = Kz_0$ and the settlement trough width can extend up to $3i = 3Kz_0$. The dimensionless parameter K varies within a wide range of 0.25 to 0.7 and it depends on soil conditions. Figure 5 illustrates the need for determination of K in assessment of the effects caused by tunnelling.

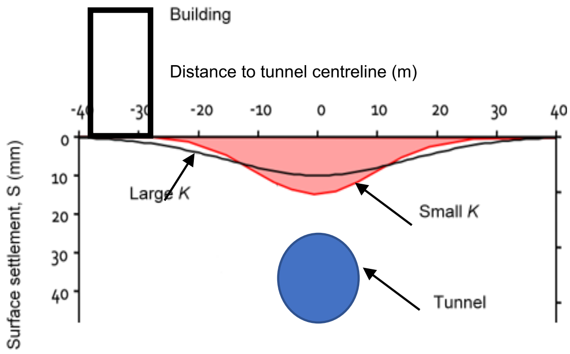


Figure 5. Influence of K to the width of the settlement curve (after [8]).

It can be seen from Figure 5, that for large K (wider settlement curve) the building will be in the influenced zone and will need to be examined for the tunnelling - induced effects. On the other hand, for small K, the building is out of the influenced zone hence there is no need to assess the tunnelling effects. Therefore, a good prediction of K is of paramount importance to determine the width of the settlement trough and hence the area affected by ground settlement due to tunnelling.

In order to make good predictions, reference database, including movements of soil caused by tunnel construction in local regions are vital. Those reference data could provide useful values of K and V_L which enable the settlement trough caused by tunnel construction to be estimated using Equation 1. A common method to determine the values of K and V_L from the field data is the non-liner approach suggested by [11].

3. The non - linear regression method

[11] proposed a nonlinear regression method to estimate parameters K and V_L. The procedure involves varying the two parameters K and V_L and calculating the corresponding sum of absolute errors (SAE). The "best-fit" is defined as the combination of K and V_L that results in the smallest SAE. The SAE is calculated as the difference between the measured data (S_M) and the empirical calculation using equation 1 (S_E):

$$SAE = \sum_{m=1}^{n} |S_E^m - S_M^m| = \left|0.313\frac{V_L D^2}{Kz_0} exp\left(\frac{-y_m{}^2}{2(Kz_0)^2}\right) - S_M^m\right| \quad (8)$$

Where: n is the total number of measurement points.

The best-fit values of K and V_L can be found by using the solver function in Excel or the curve-fitting application in Matlab. The two main advantages of non-linear regression method are:

- It is straightforward which involves non-linear regression calculation to obtain K and V_L;

- The results are objective as they are based on the calculated SAE.

However, the non-linear approach does not present the reliability of the obtained values. This paper seeks to improve this aspect by proposing a method to quantify and assess the reliability of obtained values using field measurements from a case study of tunnel construction in Ho Chi Minh city.

4. The case study in Ho Chi Minh city

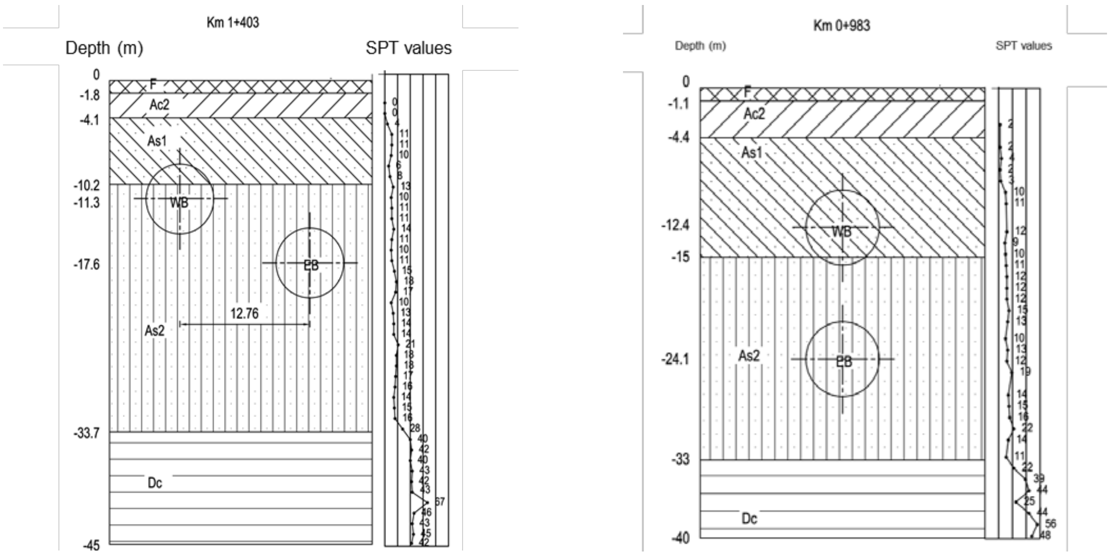
The total length of the line is 19.7km which includes 781m of twin tunnels. The East-Bound (EB) tunnel was constructed first and the West-bound (WB) tunnel was constructed later. The purpose of this paper is to assess the reliability of the determined K and V_L values hence only data from the EB tunnel will be used to avoid the effects of interaction between the two tunnels.

Field measurement at the two locations km 1 + 403 and km 0 + 983 were chosen to be studied in this paper. The reasons being was in these areas, the monitoring points were far from existing buildings hence soil settlement was caused by tunnel excavation only and the effects of surface structure were negligible. This makes settlement values suitable for greenfield analysis.

The ground, at those two locations, comprises of five different layers as illustrated in figure 6 and described below:

- Fill: sand, clay, gravel, brick, concrete, yellowish grey, yellowish brown;
- AC2 (Alluvial clay): fat CLAY, bluish grey, very soft to soft;
- AS1 (Alluvial sand): silty SAND/clayey SAND, somewhere with organic, gravel, blackish grey, bluish grey, brownish grey, yellowish grey, medium stiff to stiff, somewhere soft;
- AS2 (Alluvial sand): silty SAND/Silty clayey SAND, yellowish grey, bluish grey, whitish grey, medium dense;
- DC (Diluvium clay): Lean CLAY/fat CLAY/clayey silt, yellowish brown, bluish grey, brownish grey, very stiff to hard.

The EB tunnel lied completely in the layer AS2 at those two considered sections. The depth of the EB tunnel at section km 1+403 and km 0+983 are 17.6m and 24.1n below the ground surface.



a) Km 1+403 *b) Km 0+983*

***Figure 6**. Tunnel arrangements and geotechnical profiles [12].*

5. Assessment on the calculated values of *K* and V_L

Calculation using the non-linear regression method were conducted that gives two pairs of *K* and V_L for the two locations as below.

- Km 1+403: *K*=368; V_L=0.15%.
- Km 0+983: *K*=0.204; V_L=0.021%.

In order to assess the reliability of the determined *K* and V_L, this paper proposes to use a factor called the goodness of fit formulated as below;

$$G = (1 - \frac{SAE}{|SoS|}) \times 100 \quad (9)$$

Where:

G is goodness of fit;

SoS is Sum of Settlement.

Table 1 presents calculated values in the non-linear regression analysis and *G* for km 1+403 in which 7 monitoring points (P1 to P7) were used.

Similarly, calculation of *G* for km 0+983 was carried out and the value of *G* was 37% with the best-fit *K*=0.204; V_L=0.021%. At this stage, it can be seen that those obtained values are not reliable due to low *G*.

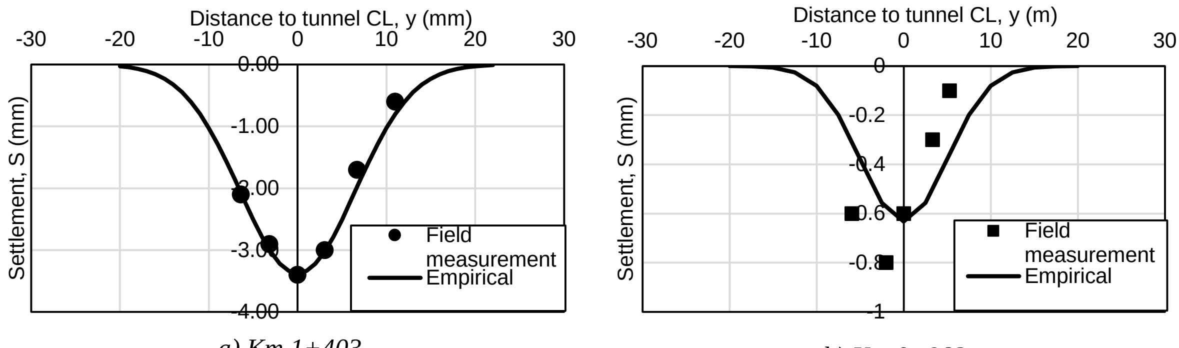
In order to illustrate the goodness of fit of the empirical settlement trough, calculated by Equation 1 using the determined *K* and V_L, with the measured data, Figure 7 compares surface settlement from field measurement and the empirical calculation at the two locations due to EB tunnel constructions.

From Figure 7.a, it can be seen that the empirical settlement trough fits well with the field data which is confirmed by the high value of goodness of fit *G*=94.5%. In contrast, for km 0+983, the goodness of fit value is low *G*=37% which reflects the poor fit of the empirical settlement trough with the field measurement (Figure 7.b).

It is important to note that the tunnel at the two locations were in the same soil layer but the *K* values determined from the non-linear regression analysis were almost two times different.

***Table 1**. Calculation values in non-linear regression method for km 1+403.*

	P1	P2	P3	P4	P5	P6	P7
Y (m)	-6.4	-3.2	0	3.1	6.7	11	14.7
S_M (mm)	-2.1	-2.9	-3.4	-3.0	-1.7	-0.6	-0.2
S_E (mm)	-2.0	-2.9	-3.3	-2.9	-1.9	-0.8	-0.3
AE (mm) (10^{-2})	9	1	14	8	22	18	5
SAE (mm)	0.81						
SoS (mm)	-14.07						
G (%)	94.5%						



a) Km 1+403

b) Km 0+983

***Figure 7.** Comparison on surface settlement from field measurements and empirical calculations (EB tunnel construction).*

This implies one of the values is not reliable. Knowing the goodness of fit *G* is beneficial to determine the reliability of the determined *K* and V_L before plotting the empirical settlement trough or adopting the *K* values for further calculation.

6. Conclusion

The original non-linear regression method offers an objective approach to estimate the two key values *K* and V_L that best fit with the field data. However, the calculation from the non-linear regression approach itself does not indicate the reliability or the goodness of fit between the empirical settlement trough and the field data.

By using the factor *G* proposed in this paper, the goodness of fit can be estimated which is simple and useful to decide if the determined *K* and V_L values are reliable and provide good fit. In addition, this method can be used to quantify the goodness of fit of the calculated settlement through for other methods such as finite element analysis with field measurement.

For analysis that involves large amount of field measurements, the simple calculation of *G* factor proposed in this paper offers robust assessment on the reliability of the *K* and V_L values obtained from the non-linear regression method❑

Acknowledgement

The authors acknowledge the Ministry of Transport of Vietnam for their funding for this research (Grant no. DT183048) and Ho Chi Minh city University of Transport for their support.

References

[1] Decision number 568/QĐ-TTg of Vietnam Government dated 8/4/2013 regarding approval of Plan of Transportation development in Ho Chi Minh city to 2020 with vision after 2020.

[2] Decision number 1259/QĐ-TTg dated 26/7/2011 of Vietnam Government regarding Master plan of the capital city to 2030 with vision to 2050.

[3] Decision number 214/QĐ-TTg dated 10/02/2015 of Vietnam Government regarding approval of Strategy for development of Railway transportation in Vietnam to 2020 with vision to 2050. Decision number 1468/QĐ-TTg dated 24/8/2015 of Vietnam Government regarding changes in Master Plan for Railway transportation of Vietnam to 2020 with vision to 2030.

[4] Chapman, D.N., Metje, N. and Stark, A., 2017. Introduction to tunnel construction. Crc Press.

[5] B.T. Le, R.N. Taylor. 2018. Soils and Foundations. Response of clay soil to three-dimensional tunnelling simulation in centrifuge models.

[6] Mair, R.J. and Taylor, R.N., 1997. Theme lecture: Bored tunnelling in the urban environment. In Proceedings of the fourteenth international conference on soil mechanics and foundation engineering (Hamburg, 1997), Balkema (pp. 2353-2385).

[7] Mair, R.J., 2008. Tunnelling and geotechnics: new horizons. Géotechnique, 58(9), pp.695-736.

[8] Wan, M.S.P., Standing, J.R., Potts, D.M. and Burland, J.B., 2017. Measured short-term ground surface response to EPBM tunnelling in London Clay. Geotechnique 67.

[9] O'Reilly, M.P. and New, B.M., 1982. Settlements above tunnels in the United Kingdom-their magnitude and prediction. Tunnelling 82. Third International Symposium, the Institution of Mining and Metallurgy.

[10] Jones, B. and Clayton, C., 2013. Guidelines for Gaussian curve-fitting to settlement data. In Underground–The Way to the Future: Proceedings of the World Tunnel Congress, CRC Press, Boca Raton, Fla (pp. 645-652).

[11] Soil investigation report for the metro line in Ho Chi Minh city, Vietnam.

[12] Dimmock, P.S., 2003. Tunnelling-induced ground and building movement on the Jubilee Line Extension. PhD thesis, University of Cambridge.

[13] Peck, R.B., Hendron, A.J. and Mohraz, B., 1972, June. State of the art of soft-ground tunneling. In N Am Rapid Excavation & Tunneling Conf Proc (Vol. 1).

[14] DeJong, M.J., Giardina, G., Chalmers, B., Lazarus, D., Ashworth, D. and Mair, R.J., 2019. The impact of the Crossrail tunnelling project on masonry buildings with shallow foundations. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, pp.1-35.

Ngày nhận bài: 14/5/2019
Ngày chuyển phản biện: 17/5/2019
Ngày hoàn thành sửa bài: 7/6/2019
Ngày chấp nhận đăng: 14/6/2019