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Design Chart of Trough Width Value for Rectangular Shaped Tunnel

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Rectangular tunnel, trough width value, PLAXIS, finite element method

Abstract

Abstract: The rectangular tunnel has proven as the best technique for depth clearance and utilizing the space of cross-section compared with the circular tunnel. In designing the rectangular tunnel, trough width parameters found from the literature mostly were designed for circular shape tunnels only. The main objective of this paper is to develop a design chart of trough width value for rectangular tunnels through a parametric study comprising a variation of tunnel size ratios using numerical analyses. PLAXIS 2D, a finite element modelling software, was used to generate rectangular tunnel models with shield support under different conditions. Developing a design chart could increase the intention of constructing a rectangular-shaped tunnel for tunnel engineers and increase the impact on green engineering. Design charts for rectangular tunnels held at depths of 4 m, 5 m and 6 m were developed and validated with field data from the literature for the potential application of trough width value that matches clayey ground conditions. Soft soil conditions may not be applicable to be applied on these charts.

1. Introduction

In the research of transportation, assessing the condition or safety of the environment is vital to prevent the occurrence of undesirable events. Tunnels fall within the realm of transportation infrastructure and demand significant focus throughout their construction phase. Tunnel excavation leads to soil stress distribution around the tunnel and causes soil at the front and above the tunnel to exert active pressure on the excavation face. The presence of structure above the ground surface and groundwater table contributes to the additional amount of pressure around the tunnel. As a result, exerted pressure at the excavation face can cause the ground around the tunnel to deform. Soil shear strength around the tunnels should be maintained in order to remain tunnel stability. This can be done by applying adequate pressure during the excavation. As a result of soil displacement, the deformation of the ground leads to settlement on the surface, which gives rise to a phenomenon known as 'settlement trough'.

Recently, rectangular shaped tunnel was reported in the literature such as [1] produced a stability design chart for unsupported wide rectangular tunnels, [2] stability of rectangular tunnel in cohesionless soil, [3] observed a racking deformation on rectangular tunnel cross-section and [4] study a ground movement profile for the underground box structure. However, none of the literature investigated the trough width induced by rectangular-shaped tunnels. A proper understanding of the trough width settlement is required to ensure the safety of the structure sitting above the ground. The increase of trough width settlement may cause more buildings to be damaged. Therefore, this research study aims on investigating the trough width settlement induced by rectangular-shaped tunnels. A dimensionless trough width design chart of a rectangular tunnel will be developed using clayey soil properties through numerical simulation in PLAXIS 2D software.

1.1 Ground Settlement Due to the Tunnelling Activities

Peck [5] introduced the prediction of settlement trough by employing the Gaussian function of normal distribution. In numerous instances of tunnel construction, the Gaussian function effectively characterized the settlement trough. This method is simple to use and widely implemented in predicting soil settlement profiles [6], [7] thus resulting in the wide usage of this empirical formula by researchers in their work. Peck [5] has produced a dimensionless chart to represent a relationship of *i* with tunnel depth in different types of soil as shown in Fig. 1. Then, according to [8] the relation between parameter *i* and tunnel depth can be represented as a vertical angle denoted as β. This angle is defined as the inclination between the vertical line and the line stretching from the spring line to the outer edge of the surface trough. The classification of the β value has been determined for various soil types using a graph generated from the correlation between *i*, tunnel radius, tunnel depth and the specific soil type. After that [9] examine the relationship of *i* and tunnel depth by using the model with and without surcharge on the ground surface. From the observation, the *i* value that appears in the model with a surcharge load is higher than the model without a surcharge load. Finally, utilizing the three-dimensional equation presented by Attewell and Woodman [10], O'Reilly and New [11] established a correlation between *i* and tunnel depth for both cohesive and cohesionless soils though the application of multiple linear regression.

To determine the maximum ground surface settlement and subsequently the transverse settlement profile, it is essential to consider the volume loss, V_l and point of inflection, *i*. Refer to Fig. 2 for visual representation. [5], [12] suggest Eq. (1) to specify the settlement profile. As indicated by Eq. (2), the settlement soil volume (V_s) situated between the settlement trough and the initial ground surface can be calculated by integrating Eq. (1).

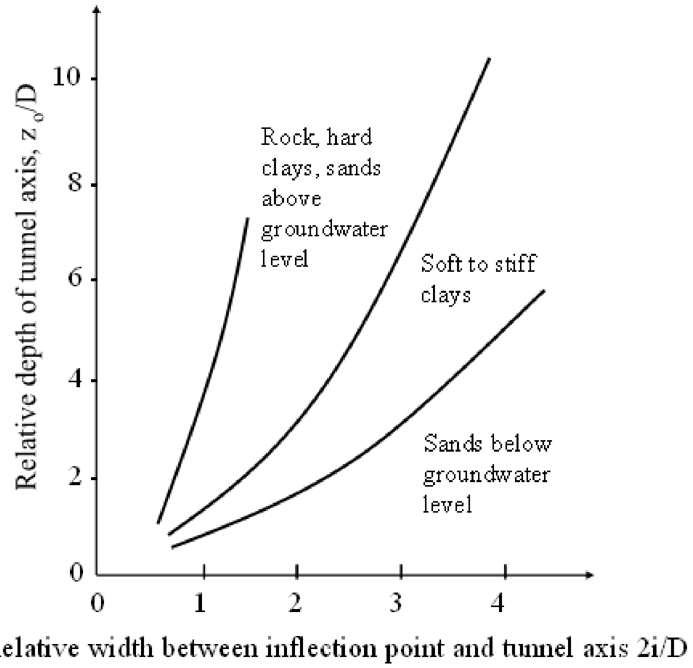


Fig. 1 *The correlation between tunnel depth and tough width [5]*

Int. Journal of Integrated Engineering Vol. 16 No. 6 (2024) p. 170-178

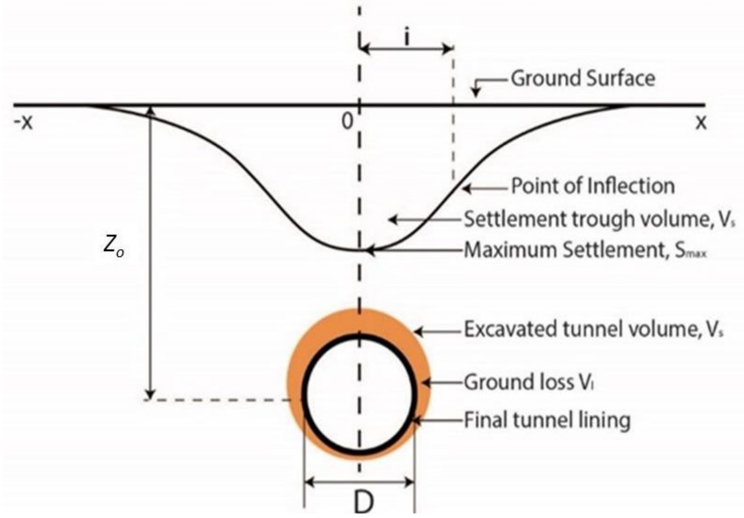


Fig. 2 *Settlement trough of gaussian form*

$$S_x = S_{max} e^{-\frac{x^2}{2i^2}} \tag{1}$$

where S_x is settlement at one point, S_{max} is maximum point of settlement, x is selected point and i is point of inflection.

$$V_s = \sqrt{2\pi}.i.S_{max} \tag{2}$$

where V_s is settlement volume, S_{max} is maximum point of settlement and i is point of inflection.

Estimation on the transverse surface settlement induced by rectangular tunnel can be done similarly to estimating on the transverse surface settlement induced by circular tunnel as shown in Fig. 3. Besides that, most of the equations developed for circular tunnels can be adopted by the rectangular tunnel model. However, the calculation of the volume of ground loss, V_t by the rectangular tunnel will be different due to tunnel geometry as it needs to be calculated using Eq. (3). The width of the settlement trough is the distance from the inflection point, i to the tunnel axis in the Gaussian distribution curve. The linear regression can be simplified as shown in Eq. (4) which suits most of the practical purposes in homogenous ground.

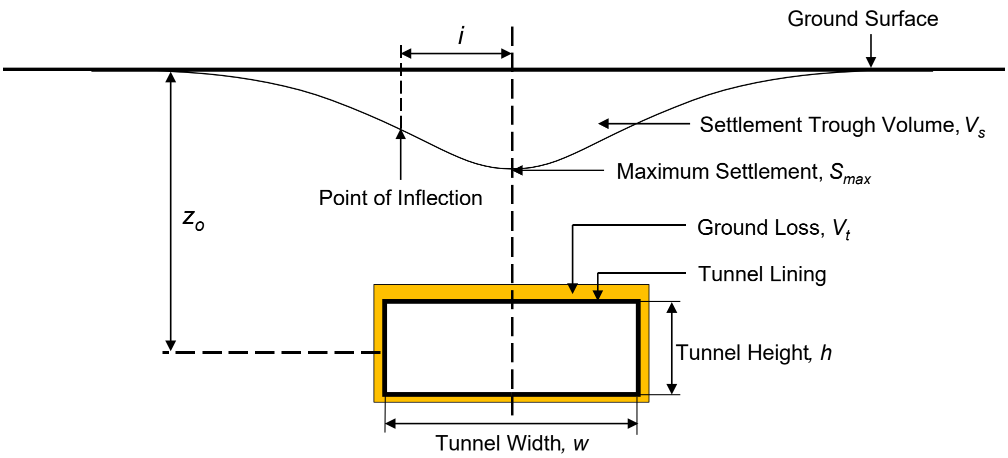


Fig. 3 *Settlement trough induce by rectangular tunnel [13]*

$$V_t = h.w \tag{3}$$

where V_t is volume of ground loss, h is tunnel height and w is tunnel width.

$$i = K.z_o \tag{4}$$

where i is point of inflection, K is trough width parameter and z_o is tunnel depth.

Numerous research endeavours have aimed to derive an equation for i in order to establish connections with various parameters. To satisfy Eq. (4), dependable values of K are necessary, and this has led to divergent values being proposed by different researchers. For instance, [14] suggested a value of 0.5 for clay soil, while [11] recommended 0.2 to 0.3 for granular soil with tunnel depths less than 10 meters, 0.4 to 0.5 for stiff fissured clay, 0.5 to 0.6 for Glacial deposits, and 0.6 to 0.7 for silty clay deposits. [15] proposed 0.2 to 0.3 for granular material above the water table, and [16] put forward 0.4 to 0.5 for stiff fissured clay, 0.5 to 0.6 for glacial deposits, and 0.6 to 0.7 for silty clay. [17] suggested 0.4 for stiff clays and 0.7 for soft silty clays. In contrast, [18] offered differing values where K equates to 0.5 for all clay soils and 0.35 for granular soils. Additionally, [19] asserted that the appropriate K value for soil encountered in the Klang Valley of Malaysia is 0.5. However, these K values have predominantly been examined in the context of circular tunnel simulations or projects. Notably, none of the aforementioned studies have specifically addressed rectangular or box tunnels when determining K values.

2. Simulation Parameter

2.1 Constitutive Model

Simulation by FEM analysis for ground behavior and tunnel lining deformation requires information such as the soil and structure properties, user-defined geometries, and constitutive soil models. The framework of formulation or known as the constitutive soil model works in describing the soil behavior during the tunnelling activities which affect the inducement of stress and strain in the soil. The Hardening Soil (HS) model is the best model for illustrating the condition of the tunnel excavation in clay soil properties. This model also shows the actual response of the tunnel lining deformation [13]. Table 1 shows the detail for each parameter adopted in the numerical model.

Table 1 *Numerical model properties*

Soil Properties	Value	Unit
Secant stiffness in standard drained triaxial test, E_{50}	13,000	kN/m^2
Tangent stiffness for initial oedometer loading, E_{oed}	13,000	kN/m^2
Unloading/reloading stiffness, E_{ur}	39,000	kN/m^2
Power for stress-level dependency of stiffness, m	0.5	-
Reference stress for stiffness, p^{ref}	100	kN/m^2
Ko-value for normal consolidation, K_o^{nc}	0.5	-
R failure ratio, R_f	0.9	-
Cohesion, c'	5	kN/m^2
Friction angle, φ'	28	degree

2.2 Analysis Method

RTBM construction method was adopted in the PLAXIS software for the rectangular tunnels with shield support as RTBM was the simplest method to be applied among other supports. The clayey soil condition was considered for the design chart. Furthermore, clayey soil properties were selected from the literature because after investigating on the tunnel construction in Kuala Lumpur, it was found that most of the areas in Kuala Lumpur were covered with cohesive soil conditions. From the design standard [20], the selected tunnel size was limited to three different heights with various widths which focused on the tunnel with motorway purpose as stated in Table 2. Hence the rectangular tunnel for motorway purposes will use a height range from 4 m to 10 m and width at a range of 5 m to 35 m.

Table 2 *Range of the rectangular tunnel size*

Tunnel Operation	Width, w (m)	Height, h (m)
Motorway	5 - 35	4 - 10
Pedestrian	5 - 12	3 - 8
Railway	10 - 18	6 - 10

Sewerage	1 - 24	1 - 10

2.3 Numerical Model for Design Chart

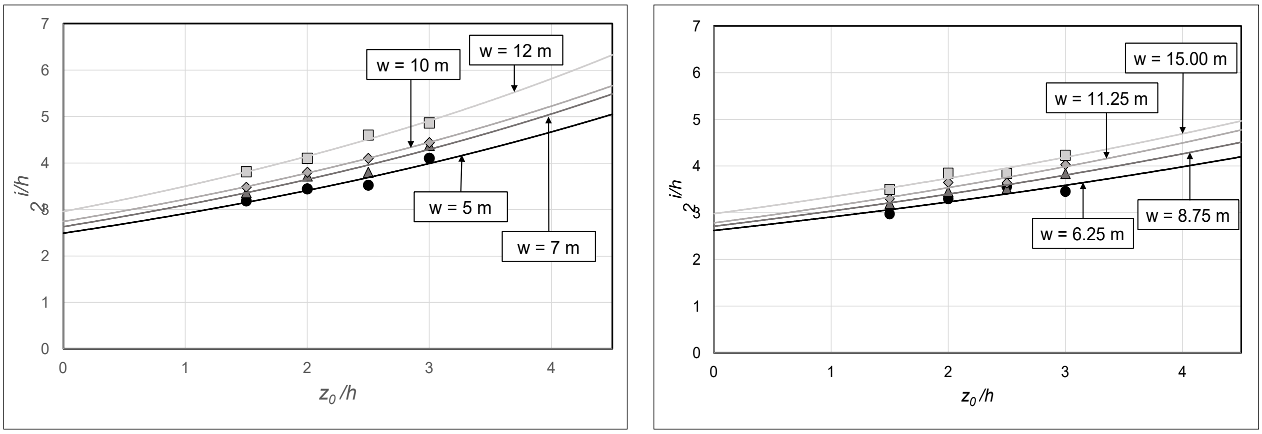
A dimensionless trough width chart will be developed which focuses on the rectangular tunnel in a clay soil property using parametric study for various rectangular tunnel model sizes listed in Table 3 at four different tunnel depths which are 1.0 h, 1.5 h, 2.0 h and 2.5 h for each model. The design chart will be produced for estimating the trough width induced by the rectangular tunnel excavation from RTBM as this parameter could affect the structure built above the ground.

Table 3 *Simulation model for design chart*

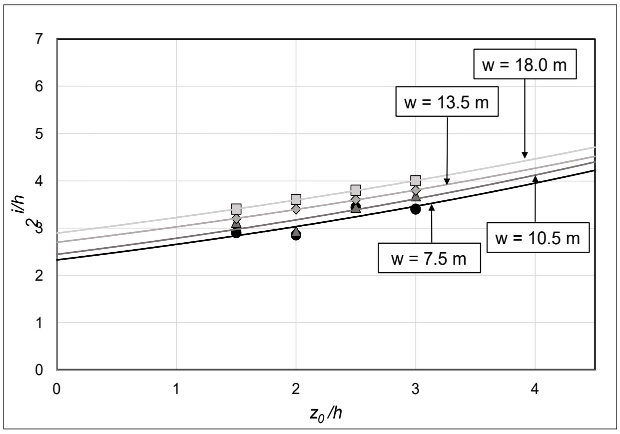
No. Model	Height	Size Ratio (w/h)
1		1.25
2		1.50
3		1.75
4	4	2.00
5		2.25
6		2.50
7		3.00
8		1.25
9		1.50
10		1.75
11	5	2.00
12		2.25
13		2.50
14		3.00
15		1.25
16		1.50
17		1.75
18	6	2.00
19		2.25
20		2.50
21		3.0

3. Design Chart

Three design charts are produced with different tunnel heights as illustrated in Fig. 4. The analysis consists of tunnel ratio (w/h) with 1.25, 1.50, 1.75, 2.00, 2.25, 2.50 and 3.00 for each tunnel with respective height of 4m, 5m and 6 m. A trendline is generated to observe the general direction of the analyses point in the chart. The graph obtain is increasing gradually which seems to be approximately similar with the pattern on the graph provided by Peck [5]. However, in order to produce a more comprehensive design chart, further work may include more onsite measurement data [21].



(a) (b)



(c)

Fig. 4 *Design chart for (a) 4 meters tunnel height; (b) 5 meters tunnel height; (c) 6 meters of tunnel height*

3.1 Applicability of Design Chart

Please The past projects were collected from the literature. However, research papers for rectangular tunnel projects with settlement field data are still limited. Fortunately, there are three research papers found to have approximate dimensions with the range parameters of the design chart.

The first paper found was about a rectangular tunnel project at the central section of Xi'an, China [22]. The rectangular tunnel with tunnel dimensions is 4.2 m x 12 m and 6.2 m clearance height was constructed at the soil properties consist of consists of backfill, new loess, saturated loess, paleosol, old loess, and silty clay. Fig. 5 illustrates a transverse settlement recorded on site which was plotted along with an empirical equation to obtain *i* value. 2% of estimated volume loss in the empirical equation gives 10.6 m of *i* value. By using the developed design chart, *i* is equal to 8.82m (see Fig. 6) while the comparison of *i* between the empirical equation and design chart obtain is 17%.

Next, the second project located at Ningbo, China by Yuanhetang was about a rectangular tunnel project constructed under the river with a 0.8 m depth [23]. Uniquely, this project installed an anti- buoyancy slab beneath the river to avoid water seepage to occur during the tunnel construction. The dimension of the tunnel was 9.1 m x 5.5 m with a 4.3 m overburden layer. RTBM construction method was adopted in this project with the combination of seven cutter heads. Fig. 7 shows the settlement data from the Yuanhetang tunnel project which matched the empirical equation, with *i* equal to 4.5 m. However, *i* value produced by the developed designed chart was equal to 8.5m (Fig. 8). The comparison of *i* between the empirical equation and the designed chart is 47% because the tunnel was constructed beneath the river which the soil was in a weak condition. This shows that the design chart is not suitable to use for the rectangular tunnel project in very soft soil layers.

Last but not least, the third rectangular project constructed based on the literature was located at Suzhoa, China with tunnel dimensions of 11.5 m x 6.9 m and 9.7 m overburden layer [24]. The geological profile for this project consists of plain fill, clay, silty clay with silt, silty sand with silt, silty sand, silty clay, clay, and silty clay with silt. The box jacking method was implemented in the project by using Earth Pressure Balance (EPB) excavation machine. From field observation, the transverse settlement profile was plotted with an empirical equation and resulted in a matching plot between these two graphs. Thus, this indicates that the proposed 2% of volume loss is reliable as illustrated in Fig. 8 which produced *i* is equal to 11.4 m. By inferring the *i* value from the empirical equation and designed chart respectively, the percentage difference between the empirical equation and designed chart is equal to 3% where the *i* produced from the designed chart was 11.73m (Fig. 9).

Int. Journal of Integrated Engineering Vol. 16 No. 6 (2024) p. 170-178

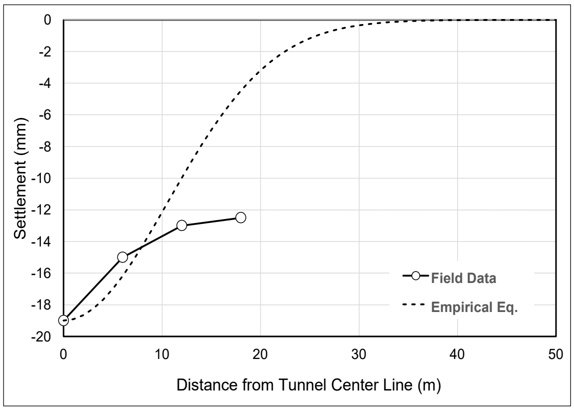


Fig. 5 *Transverse settlement profile from field monitoring*

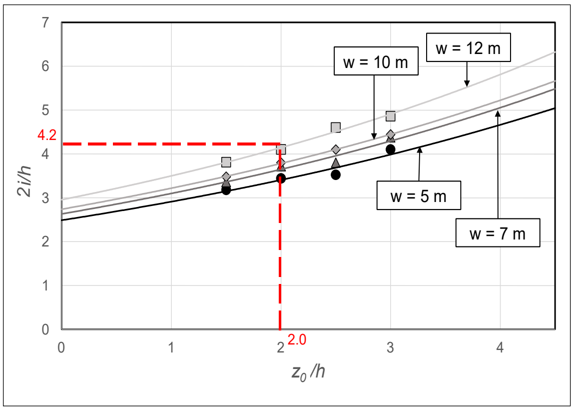


Fig. 6 *Validation of design chart of 4 meters tunnel height from field settlement*

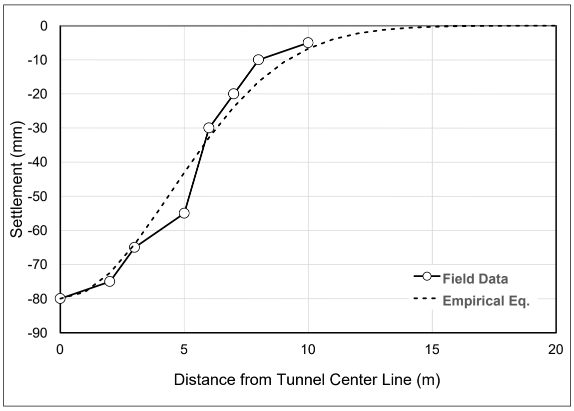


Fig. 7 *Transverse settlement profile from field monitoring*

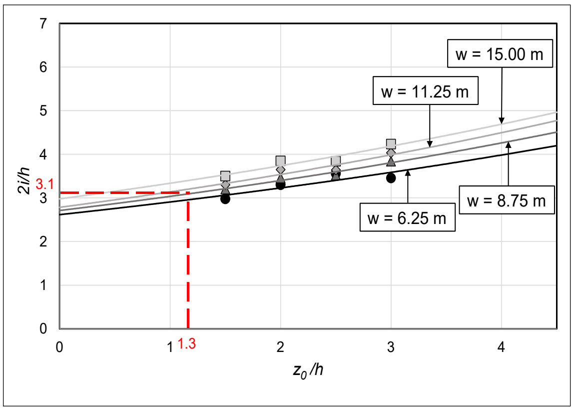


Fig. 8 *Validation of design chart of 5 meters tunnel height from field settlement*

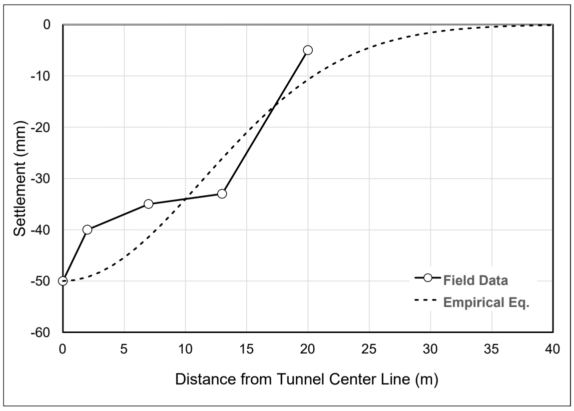


Fig. 9 *Transverse settlement profile from field monitoring*

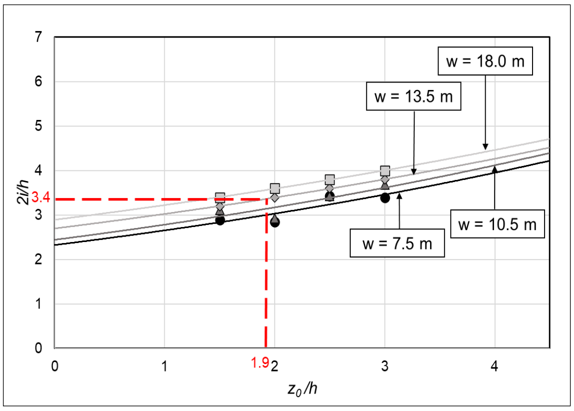


Fig. 10 *Validation of design chart of 6 meters tunnel height from field settlement*

4. Conclusion

Study had found that the design chart obtained from numerical analysis was very promising because the trough width increased considerably with overburden depth. The design chart also proved that very soft soil conditions may not be suitable to be adopted. Moreover, the developed design chart may assist tunnel engineers to conduct a preliminary checking on the risk of ground subsidence. The ground settlement estimation is vital due to involvement of public activity and structure sitting above the ground. Therefore, proper theory for rectangular shape tunnel is required. These design charts will be very useful for tunnel engineers for estimating the trough width value which could simplify the tunnel analysis work.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Yusoff Mohd Nasir, Hisham Mohamad;* ***data collection:*** *Muhammad Yusoff Mohd Nasir;* ***analysis and interpretation of results:*** *Muhammad Yusoff Mohd Nasir;* ***draft manuscript preparation:*** *Muhammad Yusoff Mohd Nasir, Hisham Mohamad, Muhammad Farid Ghazali, Muhammad Shafiq Aiman Ahmran. All authors reviewed the results and approved the final version of the manuscript.*

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