



Determining the minimum distance between centers of two parallel tunnels to apply the Law of Super Position in order to calculate subsidence by using the software FLAC 3D

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ABSTRACT

Due to the development of cities as well as rapid population growth, urban traffic is increasing nowadays. Hence, to improve traffic flow, underground structures such as metro, especially in metropolises, are inevitable. This paper is a research on the twin tunnels Of Isfahan's metro between Shariaty station and Azadi station from the North towards the South. In this study, simultaneous drilling of subway's twin tunnels is simulated by means of Finite Difference Method (FDM) and FLAC 3D software. Moreover, the lowest distance between two tunnels is determined in a way that the Law of Super Position could be utilized to manually calculate the amount of surface subsidence, resulted by drilling two tunnels, by employing the results of the analysis of single tunnels without using simultaneous examination and simulation. In this paper, this distance is called "effective distance". For this purpose, first, the optimum dimensions of the model is chosen and then, five models with optimum dimensions will be analyzed separately, each of which in three steps. The results of analyses shows that the proportions (L/D) greater than or equal 2.80, the Law of Super Position can be applied for prediction of surface subsidence, caused by twin tunnels' construction.

Keywords: surface subsidence, twin tunnels, finite difference

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INTRODUCTION

The metropolitan subway construction and completion offers many benefits including improvement in accessing to workplace, shops and recreational facilities, ease of travel by reducing the time and cost of travel, and environmental benefits. Generally, creating such a system results in increasing traffic speed by 2.5 km/h. Even though this augmentation is tiny for a vehicle, the total amount of time saving is noticeable. This system saves 50% of passengers' time in comparison with current street network [1, 2]. The purpose of this paper is to determine the minimum effective distance or necessary distance between centers of both parallel tunnels in order to use Law of Super Position in calculating surface subsidence in Isfahan metro's midsection between Shariaty station and Azadi station. For this aim, FLAC 3D software is used because of its validity in results related to the rocky-soil environments. This software is able to model every kind of tunnels, uploads, and etc. First, in this software, an initial mesh generator model of the environment is created by using commands which create meshes. Then, the appropriate boundary conditions, the geotechnical properties of the geological layers, the initial stress of surface, and the condition of underground water will be added to the model. Afterwards, the model will be analyzed to reach the initial equilibrium. Finally, the drilling operation will be simulated and the drilled model will be analyzed to achieve desired results including the deformed meshes, horizontal and vertical displacements, stresses, and etc.

Introduction of Isfahan metro's twin tunnel project:

The first phase of Isfahan's subway starts from Kaveh Street and continues to Sofeh Terminal. In this path, soil changes and for digging, TBM is used due to alluvial nature of the soil from Sofeh Terminal to Zayandehrood River. Moreover, because of expansion of rocky ground from Chaharbagh bala Street to Azadi Square and then to Sofeh Terminal, the tunnels are dug by Road Header and by means of Austrian tunneling method (NATM). In fact, in this path, digging is performed by two steps in which first step (Head) and second step (Bench) are done with height 4.5 and 2.5 meters, respectively. In this section of path, the rocks are from different types, but the dominant rock type of this path is the type of shale and sandstone periodically; therefore, in the present study, the rock type, shale and sandstone, is denoted by Jssh. Also, alluvium with approximate thickness of 13 meters is existed on the shale layer. Strength parameters of both layers are determined in Table (1) [2,1]. The table's information [1] is achieved by Hoyaux et al. method GSI-2002 [4].

Table (1): Strength parameters of existed material in the Isfahan metro's twin tunnels

Material	γ (KN/m ³)	ϕ	σ_c (MPa)	C (kPa)	ψ
Alluvium	18	0/3	65	50	35
Jssh	26	0/3	1250	110	40

modelling:

The model consists of a pair of twin and parallel tunnels which are the form of double-arch with diameter of 7 meters and depth of 10.5 meters. The distance between two tunnels' centers is equal to twice of tunnel diameter i.e. 14 meters. In this tunnel, the ration H/D (H is the distance between tunnels' center and earth's surface, and D is tunnel diameter) equals to 1.5, indicating a surface tunnel. The distance between tunnels' crown and the earth's surface and between tunnels' center and the earth's surface are equals to 7 and 10.5 meters, respectively. Since twin tunnels are examined in this case of study, in order to consider interaction between tunnels and their impact on optimum dimensions of the model, it is necessary to contemplate real characteristics and avoid considering just one tunnel because of geometrical symmetries. Figure (1) depicts geometrical features of studied model.

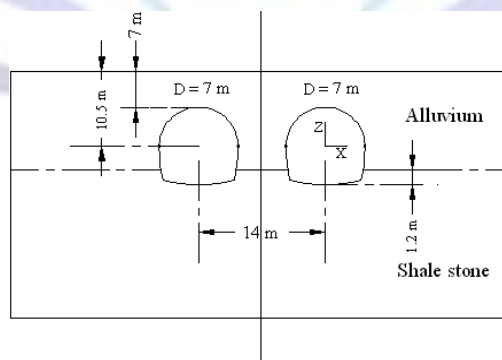


Figure (1): Geometrical features of studied model

Mohr-Coulomb model is the model which is used in this case, and this is the responsibility of the user to figure out how to determine the type of the reticulation. The user must create the best possible reticulation for the model by distributing elements among the network appropriately as well as selecting logical values for elements' dimensions. The created network is shown in Figure (2) for half of the models of this research. As it can be seen, because of the more stress and strain differences around the tunnel, elements are chosen by smaller dimensions in these parts to illustrate differences better. In

addition, in order to obtain more accurate answers, in parallel with spending least necessary time required for equilibrium, the proportion of length to width of elements is considered as unit in the surrounding areas of the tunnels.

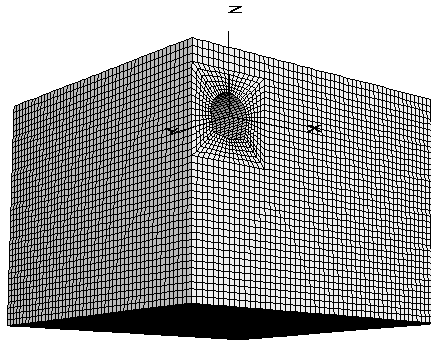


Figure (2): Reticulation of half of the studied model by FLAC 3D. Groundwater level is approximately at the depth of 30 to 35 meters below the surface. As a result, in this case of study, water existence is not considered. The traffic load (1.2 t/m) which is equal to a layer of alluvial soil with thickness of 60 centimeters is contemplated as symmetrical uniform load on both sides of the tunnels. Considered distance from tunnel's center for traffic load is represented by Figure (3).

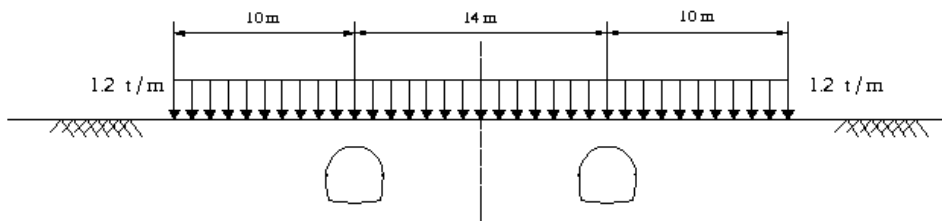


Figure (3): Considered distance from tunnel's center for traffic load

Determining the optimum dimension of the model:

In making the model geometry, the distance between boundaries of the model should be considered so that the impacts on the results are negligible. Because geotechnical issues often occur in a semi-infinite environment, thus the model used to study the actual system should be made to simulate the semi-infinite geometry of the system. If the dimensions of the model to simulate the semi-infinite environment are opted too large, the number of nodes in the model, and consequently the computation time is very high. Small-scale model is also inconsistent with the simulation of the semi-infinite environment. Therefore, in any specific problem with the different components of the model, some values are existed for model's dimension, for larger size of which, the system response will not change. These values of the model are called optimum dimension of the model.

According to the definitions of this study, in the analysis performed using the software FLAC 3D, to investigate the effect of model size on the response of the system, the vertical displacement (subsidence) in the model, representing the surface located above the excavated tunnels, is studied in the region which is defined by Pack in 1969 and in accordance with Figure (4). What is certain is that the optimal size are the size dimensions for which for values larger than those dimensions, the value for the variation of maximum vertical displacement (subsidence) is zero or negligible in the model.

In this study, by the Peck formula (1969), the range of the estimated distance is 14 meters from the center tunnel, and to ensure the complete elimination of the subsidence, the distance of 17 meters is considered in models [5,6,3].

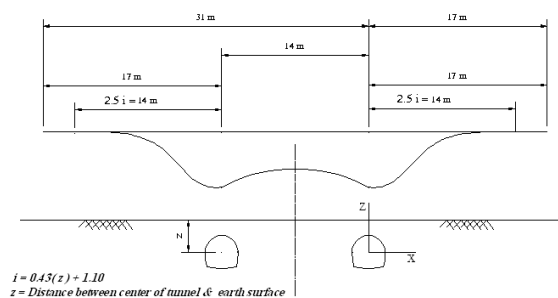


Figure (4): The curve of surface subsidence caused by tunneling and the range considered in this study to calculate the surface vertical displacement (subsidence). Pack (1969)

In this study, to investigate the effect of model size on the response of the system, the vertical and horizontal stress distribution are studied along the x-axis within width of the model. It is obvious that for larger

values of the scale dimensions, if vertical and horizontal stress distribution within width of the model are constants (vertical and horizontal stress variation within width of the model equal to zero) and equal to in-situ stress in the model, then they can be considered as optimized dimension for the model.

The analysis performed using the software FLAC 3D, nine models with different widths is used. Dimensions of the models are shown in Table (2). It is noticeable that by previous researches, 5 to 5.5 times the tunnel diameter seems appropriate for height of the model. In this study, in order to ensure greater certainty, the heights in all models from the highest to the lowest model level is considered 5 times the tunnel diameter i.e. 38.5 meters.

Table (2): Dimension features for considered models to determine optimized dimensions by the software FLAC 3D.

Horizontal distance from the tunnel wall diameter $\frac{B}{D}$	total width of the model.	Horizontal distance between the vertical lines Tadyvarh tunnel	
2/5	56	Diameter tunnel5/2	first model
3	63	Diameter tunnel3	second model
3/5	70	Diameter tunnel5/3	three model
4/5	84	Diameter tunnel5.4	four model
5	91	Diameter tunnel5	five model
5/5	98	Diameter tunnel5.5	six model
6	105	Diameter tunnel6	seven model
6/5	112	Diameter tunnel5/6	eight model
7	119	Diameter tunnel7	nine model model

The maximum values for subsidence calculated by the software FLAC 3D is shown in Figure (5) for nine models with above aforementioned features. As seen in this figure, at distances greater than five times the diameter of the tunnel (the fifth model), changes in the calculated maximum subsidence are diminutive and finally become zero.

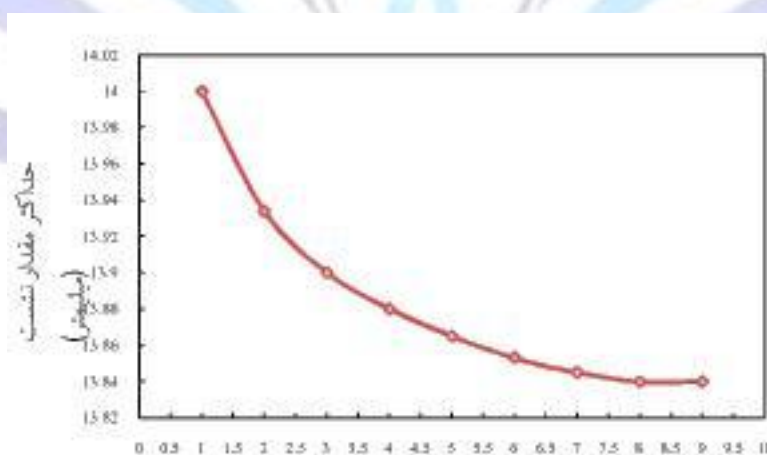


Figure (6) depicts horizontal and vertical stress distribution at different distances from the wall of the tunnel along the x-axis. As seen in these figures, at distances greater than five times the diameter of the tunnel (the fifth model), horizontal and vertical stress distribution are constants within model width (vertical and horizontal stress variation within width of the model equal to zero) and equal to in-situ stress in the model

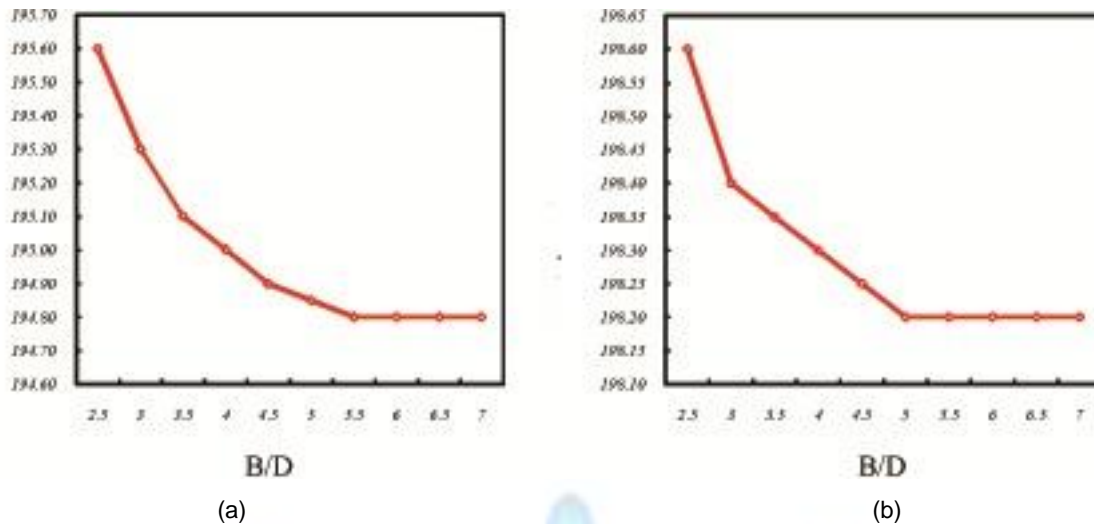


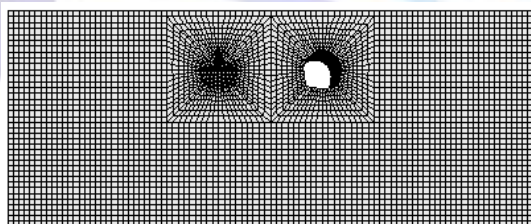
Figure (6): Distribution curve (a) vertical stress and (b) horizontal stress along the x-axis at different distances from the wall of the tunnel

Determining the effective distance:

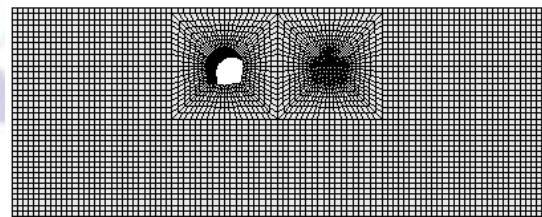
In three-dimensional twin tunnels being drilled by the above process, the interaction between the tunnels is inevitable. On the other hand, subsidence created on the surface are strongly influenced by these interactions; therefore, three-dimensional tunnel drilling as well as interaction effects created on the surface subsidence values should be examined in three separate steps. First, excavation of each tunnel has to be investigated independently. Then, the study of drilling two tunnels simultaneously will be included. Eventually, the amount of surface subsidence at each step will be extracted and analyzed. It can be very time consuming depending on different models and sizes. Since the interaction created between twin tunnels is directly related to the distance between centers of the tunnels [7], so the effective distance can be determined in a manner that minimizes the amount of interaction and utilizes the Law of Super Position to calculate the amount of surface subsidence created by drilling of two tunnels.

In order to evaluate the aforementioned distance in a way that the Law of Super Position makes it possible to manually calculate the amount of surface subsidence created by drilling both tunnels, five models, each of which in three steps, were separately analyzed as follows. After establishing equilibrium in the model, East tunnel and subsequently Western tunnel were drilled similar to complete section. In the end, drilling was carried out simultaneously on both the east and west tunnels and surface subsidence values for the three phases were separately represented and subsequently were drawn.

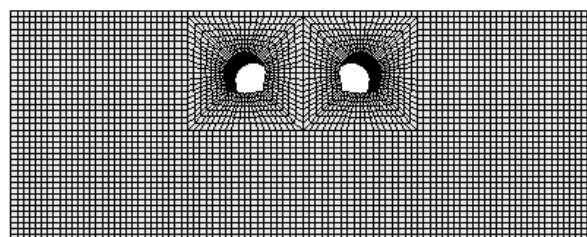
The proportion L/D in these models is equal to 2.30, 2.60, 2.80, 3.10, and 3.40 respectively. Details which are included in the model such as mesh generator mode, the ratio of length to width of elements, fulcrum condition and how to apply it, amount of traffic and how to apply it, and geotechnical properties of the materials are considered the same for all the models. For instance, three considered steps to analyze model with L/D equals to 2.60 is shown in Figure (7).



(b)Excavation of East tunnel



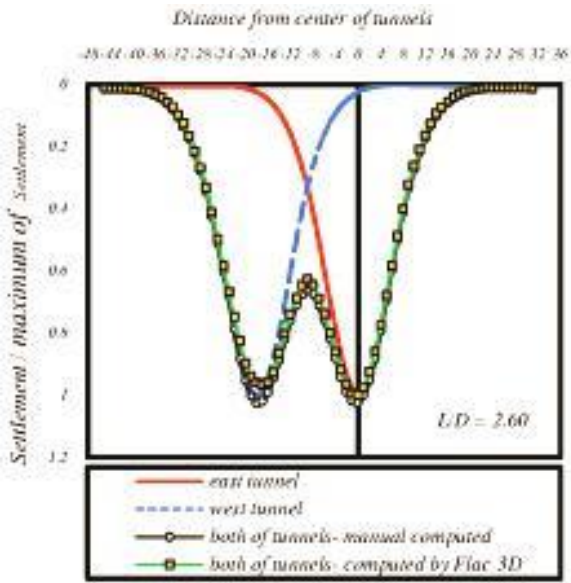
(a)Excavation of West tunnel



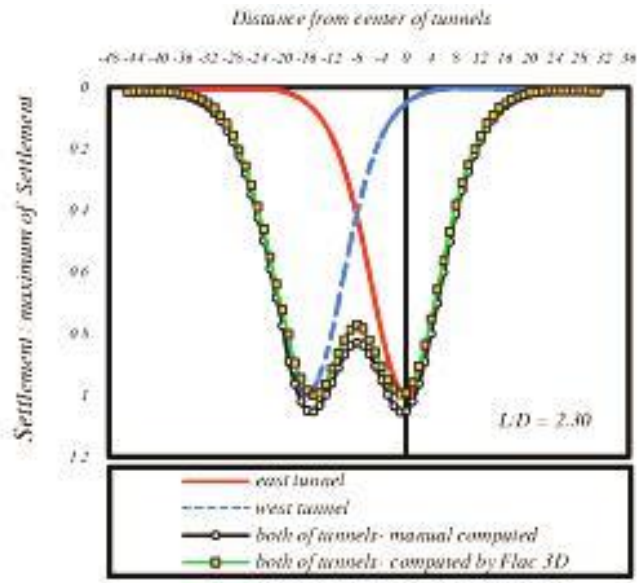
Excavation of both tunnels simultaneously(c)

Figure (7): Three considered steps to analyze model with L/D equals to 2.60

Figures (8a)-(8e) shows the results of analyses conducted on three aforementioned steps on five models with L/D equal to 2.30, 2.60, 2.80, 3.10, and 3.40 respectively



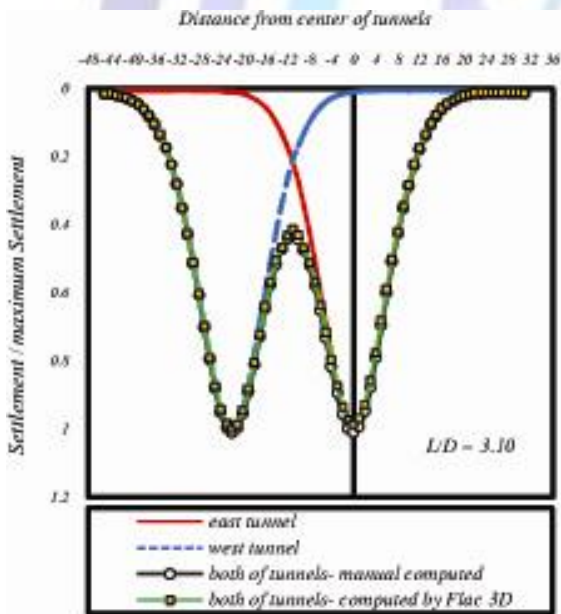
8(a)



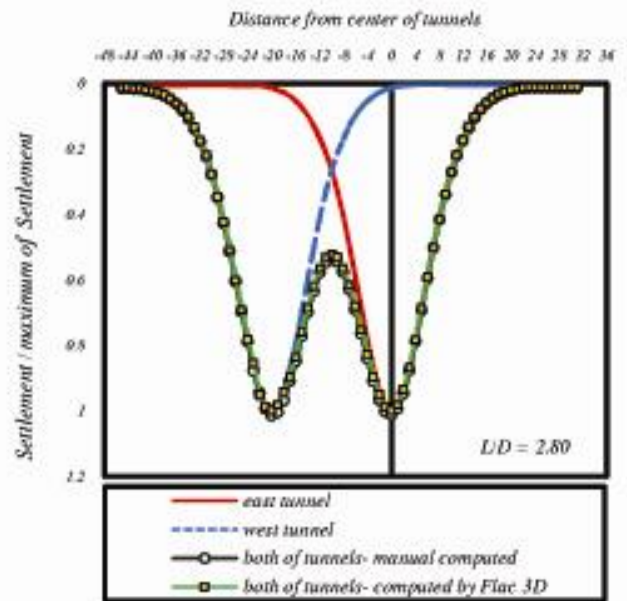
8(b)

Figure (8a): analyses results with L/D=2.30

Figure (8b): analyses results with L/D=2.60



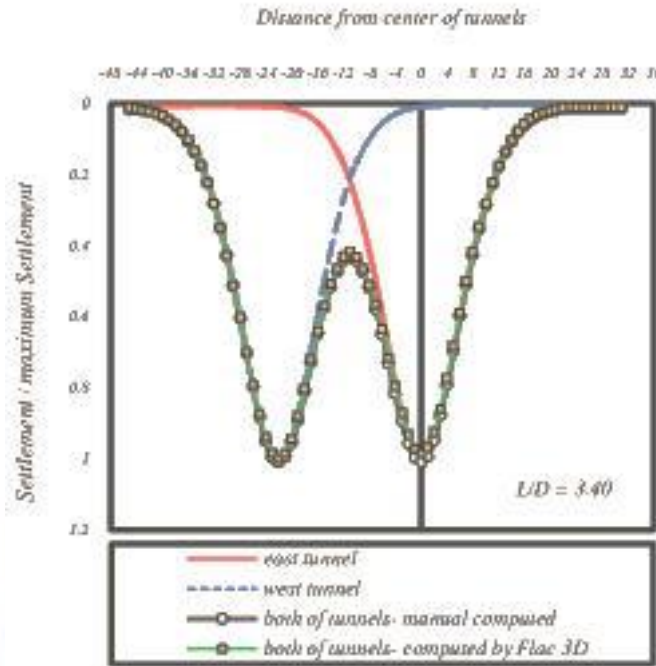
8(d)



8(c)

Figure (8d): analyses results with L/D=3.10

Figure (8c): analyses results with L/D=2.80



8(e) Figure (8e): analyses results with $L/D=3.40$

Analysis of results:

Based on performed analyses, we can conclude that:

As it can be seen from Figure (6), in distances greater than 5 to 5.5 times the tunnel diameters, vertical and horizontal stress distribution within width of the model are constants (vertical and horizontal stress variation within width of the model equal to zero) and equal to the value of in-situ stress in the model. In addition, based on Figure (5), in these distances, changes in the calculated maximum subsidence are negligible or become zero. Thus, the fifth model with W/D equals to 13, in which vertical borders is five times the size of the tunnel diameter away from the wall of the tunnel, can be considered as a model with optimum dimensions. Figure (9) is a schematic overview of the model selected as the optimal model.

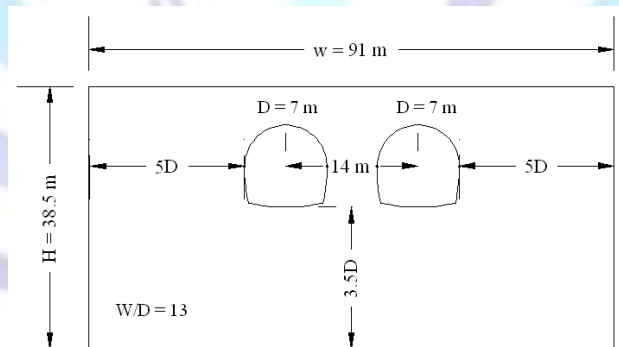


Figure (9): Geometric dimensions for optimal model in this research.

As it can be seen from Figures (8a)-(8d), the curve of surface subsidence, calculated manually by applying the Law of Super Position, becomes gradually closer to that of calculated by software such that if the ratio L/D is greater than or equal to 2.80, then these curves become matched. This, in turn, shows that for ratios L/D greater than or equal to 2.80, the Law of Super Position could be applied to predict surface subsidence caused by constructing twin tunnels. Also, it can be concluded that the parameter Z/B is applicable to evaluate interactions between twin tunnels, where Z denotes the distance between tunnel ceiling and Earth's surface and B denotes the distance restricted between two tunnels.

Previously, by using FEM results, Hoyaux and Ladanyi (1970) claimed that if the ratio of distance between tunnel centers to tunnels diameter is greater than 2.70, then the Law of Super Position can be utilized to predict surface subsidence caused by twin tunnels drilling [6]. This confirms the existence of a close adaptation between results in this study and the results of previous research.

In 1995, Adachi et al. conducted experiments on two-dimensional shallow and twin tunnels in sandy areas and achieved the same result that is reached in this research about parameter Z/B [7].



CONCLUSION

In the distances greater than 5 to 5.5 times the tunnel diameter, vertical and horizontal stress distribution within width of the model are constants (vertical and horizontal stress variation within width of the model equal to zero) and equal to the value of in-situ stress in the model.

In the distances greater than 5 to 5.5 times the tunnel diameter, changes in the calculated maximum subsidence are negligible or become zero. Hence, the model with W/D equals to 13, in which vertical borders is five times the size of the tunnel diameter away from the wall of the tunnel, can be considered as a model with optimum dimension.

For ratios L/D greater than or equal to 2.80, the Law of Super Position could be applied to predict surface subsidence caused by constructing twin tunnels.

The parameter z/b is applicable to evaluate interactions between twin tunnels, where Z denotes the distance between tunnel ceiling and Earth's surface and B denotes the distance restricted between two tunnels

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