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Comparing the excavating effect of single and twin tunnels on the earth surface settlement by numerical methods

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ABSTRACT

Nowadays due to increasing rate of urbanization, population compaction and construction in Iran, the issue of construction of underground tunnels become the center of attentions, due to it's capability to obviate the problems regarding transportation, water transmission and substructure structures. In this way, studying about the right placement, procedure of excavating tunnels and it's possible effects on superstructures specially an ancient buildings are very important and vital. In this research, the settlement of a single tunnel excavated in the depths of Isfahan city (Cultural capital of Islam world) in Iran has was studied, using the finite element program PLAXIS, then the results of this numerical analyze was compared with the data obtained from field instrumentations, Finally these results were generalized to twin tunnels. In the next stage, after studying the effect of spacing between twin tunnels over these settlements, those quantities, which are greater than the allowable settlement and their situation were recognized. It is obvious that this problem will highlight the importance of Following a good and reliable design process.

Keywords: Settlement, Twin Tunnels, Numerical Method, PLAXIS

1. INTRODUCTION

The approach to growing use of tunnels to facilitate transportation in busy and crowded parts of cities has brought about deflection in soil mass and eventually in ground surface. Among the features of urban tunnels, their less surcharge depth, loose ground of towns, large span of these areas and the buildings on the stations are important, All of them make the control of shallow settlement and maintaining stability in the underground spaces very difficult. Settlements due to tunnel excavation, can cause serious damages to the neighboring structures.

In this study, we examined single tunnels by numerical method and twin tunnels by computer modeling and accurate instrumentations. The researches on comparing the effect of single tunnel and twin tunnels on settlement of ground surface has been limited. In Iran, after the growing trend of subway tunnel excavation, in urban regions, irreparable damage of ground surface settlement on building and ancient monuments particularly in Isfahan and Siyo-Se-poul, are noticeable [Fig 1] .

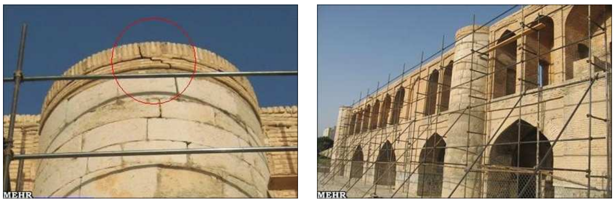


Fig 1: Damage to Siyo-Se-Poul, a worldly recorded monument due to settlement of ground surface.

Perhaps Terzaghi's report[1] is among the first reports that show the effect of soil type in transferring settlement to ground surface. Regarding coarse grained soil, he believed that all ground displacement in tunnel site owing to dilation gradually disappear to ground surface. However in clay layer, this effect is less clear mostly due to lack of volume change and soil layer which are influenced by cohesion.

Peck(1969) presented a comprehensive report containing general collection of executive operation of tunnel in soft ground. In his detailed examination, he divided settle able ground into four categories. Then for each of soils mentioned, measurements for tunnels situated in these soils[12]. He showed that the cure of ground surface settlement to tunnel excavation has normal distribution and presented a relation for the profile of settlement as follows:

$$S(x) = S_{max} \times \exp(\frac{x^2}{2i}) \qquad (1)$$

This equation has no theoretical foundation and chosen because of its similarity to experimental form of settlement. In i and S_{max} were determinant and a lot of research was done to determine them amounts and many suggestions were made to calculate them. Most of the studies are to modify determine i. Another important parameter is S_{max} [Fig2]. To achieve a relationship to calculate the amount of this parameter, a parameter called ground loss is defined ,which is in fact equals to contraction of tunnel span. In clay soils, the condition of undrained is governed during tunnel excavation, Therefore the contracted volume at tunnel's span, equals to volume of clay soil on ground surface. The amount of name it, V_L follows as eq.(2)

$$V_L = \frac{4V_s}{HD^2} \qquad (2)$$

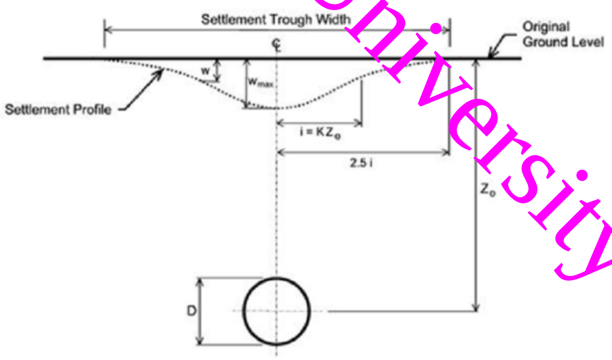


Fig 2: Curve of ground surface settlement due to tunnel excavation [12]

Where D is diameter of tunnel and V_L is reduction of ground volume relative to excavation. V_L was calculated as a percentage of settlement of volume in ground surface to tunnel volume per unit of length. Vs is the total volume of ground surface settlement and is determined by integrating the relationship eq.(1) as in eq.(3):

$$V_S = \sqrt{2\pi \times I S_{max}} \qquad (3)$$

By combining eqs.(2) and (3) and by regarding $I = KZ$, S_{max}

$$S_{max} = \frac{0.313VL^{D^2}}{KZo} \qquad (4)$$

In this equation, S_{max} is the maximum ground settlement above tunnel axis, S_x ground surface settlement to the distance of x relative to tunnel symmetry axis and i is the landmark of the curve.

Although this equation has no theoretical foundation, it has been chosen due to its similarity to experimented values of settlement. As it was seen, i is an important parameter in showing curve width[12].

Sagaseta(1987) [15] presented a solution to determine stress-strain behavior in an isotropic homogeneous environment while the incompact able soil and excavation is near ground surface. The relation which he proposed for settlement shape in plain strain state, in equations (5) and (6):

$$s_{xo} = -\left(a^2 x\right)/\left(x^2 + h^2\right)$$

Horizontal displacement at ground surface (5)

$$s_{xo} = -\left(a^2 h\right)/\left(x^2 + h^2\right)$$

Settlement at ground surface (6)

In this equations (a) is tunnel's radius, and (h) is the depth of tunnel's axis. Because of incompatibility of soil the Poisson coefficient is 0.5 presented a linear elastic analysis for a tunnel in an isotropic environment. They use elasticity theory and approximate method of Sagaseta [15]which is even usable for compactable soils with arbitrary amounts of Poisson coefficient. Their solution that is the generalized method Sagaseta, considers oval deflection of tunnel section [16].

Another factor that is defined in different condition of ground settlement is ground loss parameter that is the percentage of the ratio of settlement volume at ground surface to tunnel volume per unit of length. Based on ground loss, gap parameter is defined as follows:

$$g = GP + U_{3D} + \omega \qquad (7)$$

In which the difference between maximum internal diameter of excavated tunnel and external diameter of tunnel lining is for circular tunnel. Equivalent 3D Deflections are, in form of elastic-plastic at the front of the tunnel and determinant of excavation quality and operation of the tunnel.

2. TUNNEL GEOMETRY

Fig 3 shows complete sections of twin tunnel of Isfahan subway. It is a two-arc tunnel that .

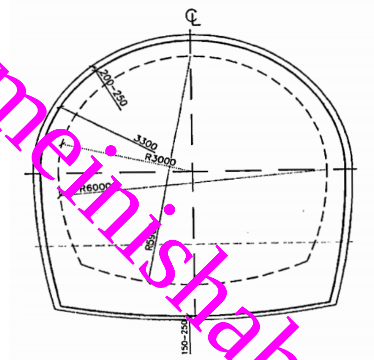


Fig 3. Sample section of the tunnel: (Center of documentation of urban trains, Isfahan (2003)

Based on the first stage research, urban train of Isfahan was designed in the form two dimensional and horse-shoe section, 7m in the middle part and its axis to axis distance is 14m.

Fig 5. is a part of target vertical section in the direction of tunnel excavation. This section was built in the width of Chahar Bagh street. Due to symmetry of boundary and environmental condition of these two tunnels, only half of geometry of target section, regarding environmental condition and loading shallow adjacent to tunnel is shown [10].

This street has two driving lines and 7m of its middle section is occupied by landscaping . The street width is assumed to be 90m in which 22.5m from each direction, is allocated to the buildings. Loading system of building is accounted 20 kP in two ways and loading of middle part (traffic loading) is supposed to be 10 KP [11] .

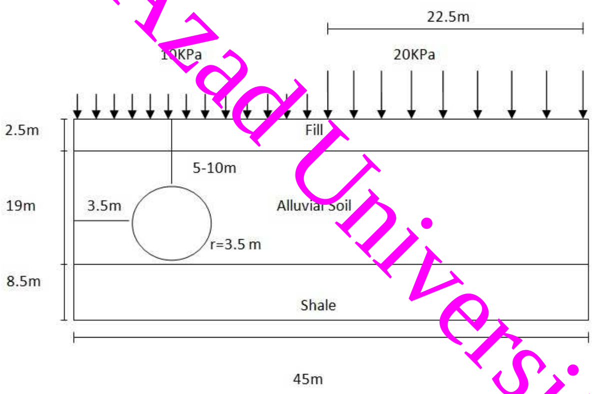


Fig 4: Vertical section of the symmetrical geometry of the tunnels and the region under study

So in the first stage, regarding the present situation, the geometry of modeled section is made in the form of two dimensional by PLAXIS software and based on Fig 5.

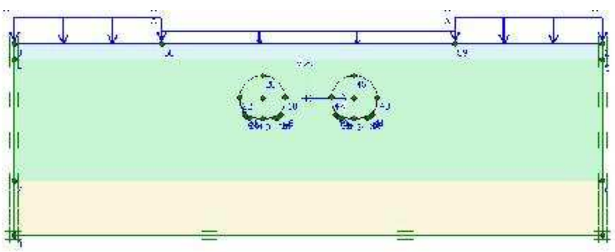


Fig 5: Modeled geometry of tunnels in software space for 5 meter depth [10]

3. DETERMINING THE SPECIFIC FEATURES OF GEO TECHNICAL MODEL

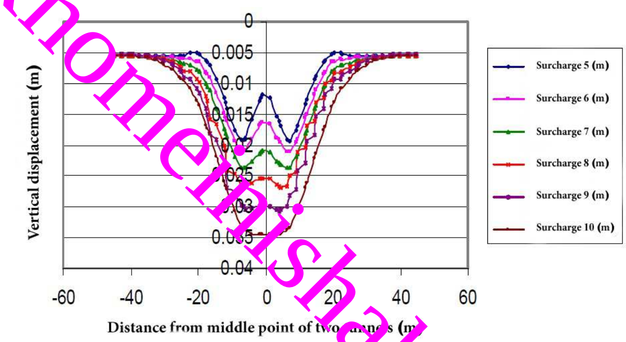
Based on present reality and environmental condition, in this model, geology layers and behavioral model of soil are assumed horizontal and coarse-grained respectively. These layers are defined in three different parts and in the form of fill materials, alluvial and silt from up to down. Geotechnical parameters given in Table 1.

Table 1: Behavioral model and geotechnical specification of soil [11]

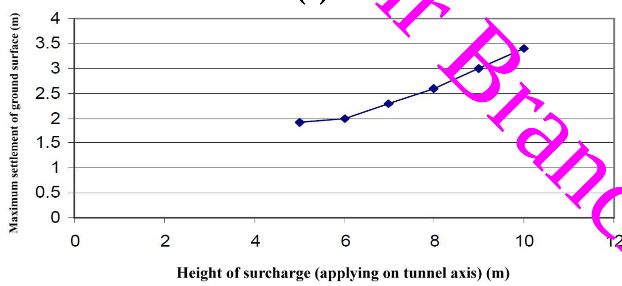
Fill Material	Alluvial	Shale	Unit	Symbol	Parameter
0-2.5	2.5-21.5	21.5-30	m	H	Depth
18	21.5	26	kN/m^3	γ_d	Unit Weight
5*10^{-7}	2.5*10^{-7}	5*10^{-6}	m/s	K_h	Permeability
1*10^{-6}	2.5*10^{-4}	1*10^{-6}	m/s	K_v	Permeability
1.5*10^{4}	8*10^{4}	1.7*10^{6}	kN/m^3	E	Young Modulus
0.35	0.3	0.3	-	ν	Poisson Ratio
15	50	0.8	kN/m^3	C	Cohesion
23	35	26	Degree	φ	Internal Friction Angle

4. ANALYSIS OF OUTPUT DATA

Based on carried out modeling in four different and subsequent phases, the results for shallow settlement, for six different states at tunnel depth are achieved. According to these results, it is clear that maximum settlement in ground surface is occurred around the tunnel axis in all states, and by increasing the surcharge of the tunnel, the interference of settlement depth of two tunnels is also increasing to the point that in surcharge state of 10m , a ditch of settlement is seen completely. The varying trend of maximum settlement relative to excavation depth of tunnel is shown in Fig 6. Ii is obvious that by increasing the depth of tunnel excavation, the amount of maximum settlement is significant [10] .



(a)



(b)

Fig6: Comparison of shallow settlement profile for six states of tunnel depth (a) - The varying trend of maximum settlement relative to excavation depth (b)[10]

The results show that:

a- In different states of surcharges(5 up to 10 meters), settlement in neighborhood of buildings in both sides of street is within the allowable of 1.0 centimeter.

b- Maximum settlement at ground surface happened at neighboring points of axis of tunnel.

c- By increasing the height of rock load on tunnels, the interaction of ditches of resulted settlement us increased.

d- the amount and area of settlement of ground surface, has direct relationship with depth of tunnel excavation.

e- It must be noted that the modeling can be done by examining three-dimensional effects of front of activities on shallow settlement amounts in neighborhood of tunnels and assess the results [10]

5. EFFECTS OF THE DISTANCE BETWEEN PARALLEL TUNNELS ON SETTLEMENT LEVEL

Instrumentation studies show that if center to centre distance of two underground space is more than three times or much as diameter, the excavation of these two spaces will not affect each other, and can be considered separately. In this section we will address this issue by numerical method and examining a tunnel.

First, the settlement from a tunnel excavation in an urban environment is modeled, and then the effect of excavating another tunnel in its neighborhood on the settlement is considered. A tunnel with 4.5m diameter and 10m depth is excavated. Before tunnel excavation the present stress in environment is in the horizontal form. It should be kept in mind that the best and optional distance for neighboring borders is the amount that, stresses at borders, has not changed just before and after the excavation and disturbance in stress contour doesn't happen[fig7][Fig8][Fig9] .

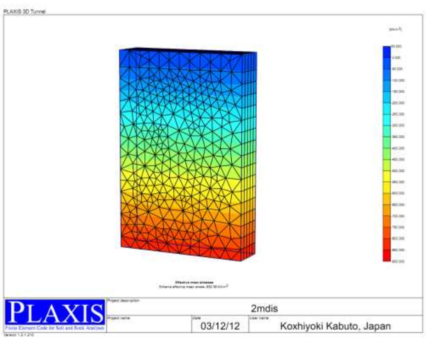


Fig7: Initial stresses before excavating the tunnel

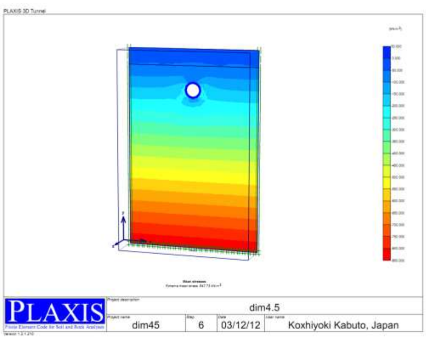


Fig8: Stress state after excavating 10m of the tunnel

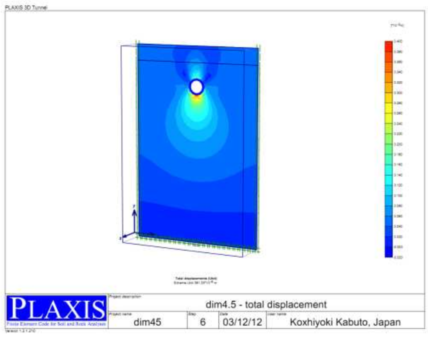


Fig9: Single tunnel total displacement

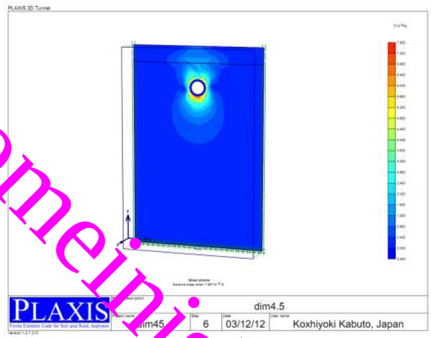


Fig10: Total strain - single tunnel

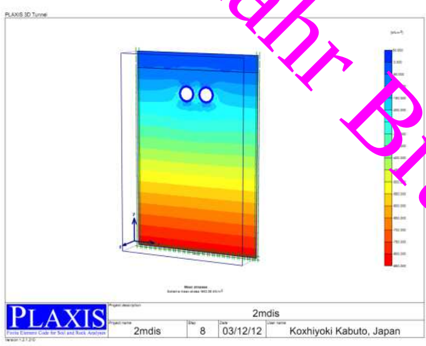


Fig11: Total stress - twin tunnel with 2m distance

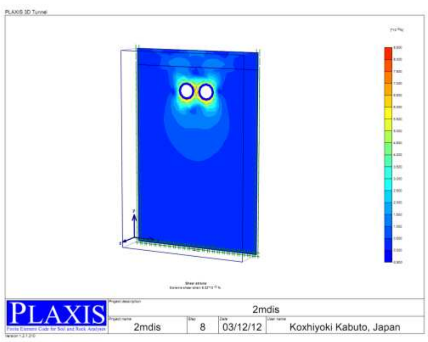


Fig12: Total strain - twin tunnel with 2m distance

After that the effect of neighboring tunnel excavation is considered with the same characteristic and in different distances. To do this, 5 states have been regarded. The distance we mean in this study is the ledge to ledge distance of two neighboring tunnels. The purpose of examining several cases (states) is obtaining optimal distance between two neighboring tunnels. At first neighboring (adjacent) tunnel is put in two meters distance from the first tunnel [Fig 10][Fig11][Fig12] .
As it can be seen, stress contours have overlap and do not act independently so that stress contour of twin tunnel is not similar to that of single tunnel, and this is also true for soil displacement around the tunnel. In the following situation tunnels are placed in 4 meter distance. In this case, although the interaction of stress and displacements contours in two tunnels are decreasing, but they still influence on each other.
In another situation, two tunnels are put in 8m distance from each other. It may be said that behavior of two tunnels is partially independent and have the least effect on each other [Fig13][Fig14] .

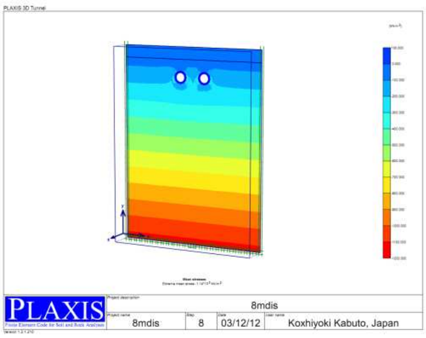


Fig 13: Total strain twin tunnel with 8m distance

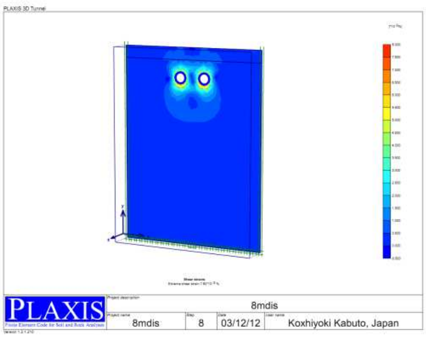


Fig 14: Total stress with tunnel with 8m distance

In another situation two tunnels are put in 10m distance and as expected, by increasing this distance and keeping the tunnels away from each other, their behavior becomes more separate [Fig15][Fig16] .

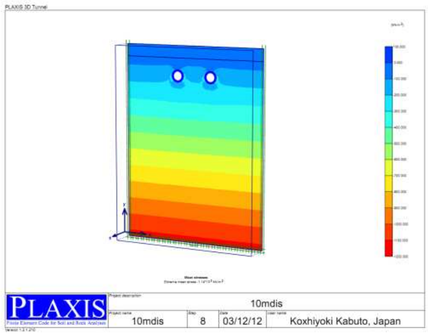


Fig 15: Total stress- twin tunnel with 10m distance

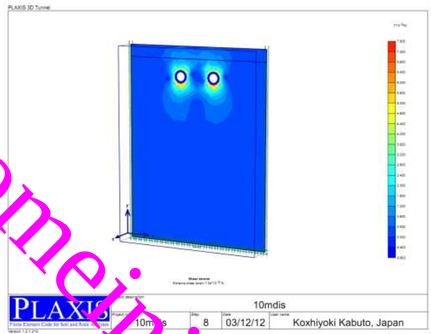


Fig16: Total strain- twin tunnel with 10 m distance

Fig 17: Total stress- twin tunnel with 12m distance

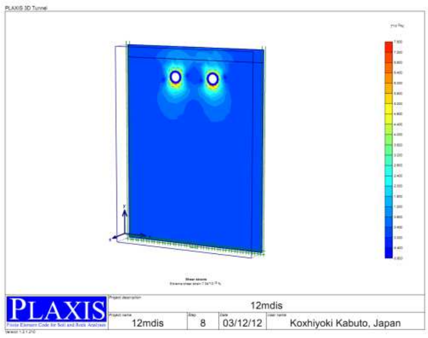


Fig 18: Total strain -twin tunnel with 12m distance

In the next situation two tunnels are put in 12m distance. As it was seen from the distance of 10m or more, stress contours and displacement around each tunnel are just alike single tunnel and next tunnel excavation has no effect on displacement and applied stresses on neighboring tunnel so that to simplify and reduce the calculation, we can examine them independently (separately) [Fig17][Fig18] .

6. COMPARING OF SINGLE TUNNEL BEHAVIOR WITH PARALLEL TUNNEL (WITH EQUAL EFFICIENCY)

In this part a tunnel with 9 m diameter (two times as much diameter as former tunnel) is excavated and studied at the same environment and condition. The purpose of this study is to examine settlement from tunnel excavation with larger diameter and its comparison with settlement from two tunnels, each one with a diameter equals to the radius of larger tunnel (with different distance from each other) [Fig19][Fig20] .

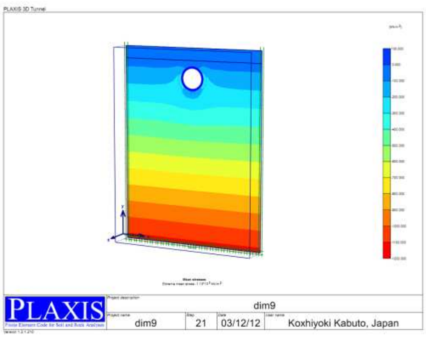


Fig 19: Total stress-single tunnel d=9m

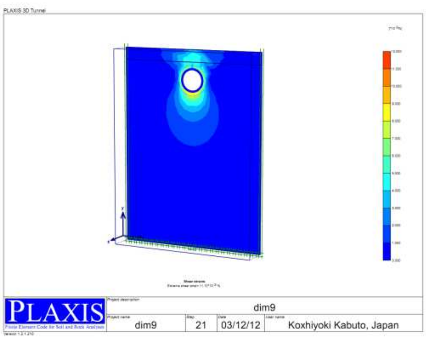


Fig 20: Total strains-single tunnel d=9m

As it was seen in comparing the displacement from excavation of two neighboring tunnels (with smaller diameter) and larger tunnel, it would be better to excavate two tunnels separately so that their distance should be in allowable level and has not much effect on displacement and settlement of ground surface.

7. CONCLUSION

In this study first the situation (condition) of urban train tunnels is studied in Isfahan and then a comprehensive review of literature is discussed about created deflections on an underground excavation and their settlement. Then general overview of stability analysis approaches are considered and regarding the use of PLAXIS software some brief description is provided. Two cross sections of subway tunnel of Isfahan were studied in which the settlement of ground surface and tunnel crown were measured by instrumentation equipments and was modeled by PLAXIS 3D. The outputs of software were adapted with measured data in above supposed stations. Furthermore, in order to examine the effect of important parameters of soil (such as cohesion, Poisson coefficient, elasticity modulus and unit weight) different diagrams of settlement were drawn and the result of created effect on the settlement of ground surface and tunnel crown was studied due to increasing or reduction of each of the mentioned parameters. Finally by modeling a tunnel with 9m diameter on one hand and two neighboring tunnels, each one with 4.5m on the other hand, and putting them in different distance from each other and observing created changes in stress contour and displacement as to using or not using two tunnel with smaller diameter instead of a tunnel with larger diameter in urban regions were explained. Regarding above –mentioned materials, following results are concluded:

1. The result from in situ measurement indicates that maximum settlement from excavation of subway tunnel in Isfahan in monitored regions is less than amount of allowable settlement (0.5 under the building as 1 inch at street level).
2. based on done research on stress contours and length displacement of 9 m diameter, and its comparison with stress contours and displacement of a twin tunnel-each with 4.5 m diameter at different distance from each other and with similar and same condition of a larger tunnel, we may say that in situations where tunnel construction is in urban regions or other sensitive places(areas), naturally any increase will have some important consequences. Using twin tunnels with smaller diameter seems reasonable and justified if the allowable distance for each of the tunnels-instead of excavating a tunnel with larger diameter- is observed.
3. In cases where the distance of two neighboring tunnels are equal or more than allowable level, we can model one of two tunnels and use results for another tunnel and generalize its result(s) to another tunnel.

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