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Study on the Extension of Critical Zones Along Tunnel Alignments and Its Impact on Structural Damage to Nearby Buildings

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ABSTRACT

Tunnel can be considered as an essential infrastructure that plays a fundamental role in transportation network namely mass rapid transit system. In recent decades, tunnel projects have increased substantially as a result of fast growth in urban development. When tunneling in urban environment, tunnels are unavoidably excavated in close proximity of neighbouring buildings. It is inevitable that tunnels will interact with building foundations and other existing infrastructures. Consequently, ground movements produced by tunnel works and namely settlement, can cause serious damage to existing buildings. Hence, it is important to improve our understanding of the critical area due to tunneling. This critical area may include the location of exceeded ground movements and stress fields. The objective of this study is to investigate the critical area in terms of ground movements produced by tunneling by using the gaussian distribution function which is the most famous approach used in practice engineering for studying settlements induced by tunnel excavation, combined with conventional damage risk assessment approach based on limit value of highest settlement. In this paper, critical area is considered as the area where tunneling can induce an intolerable damage to overlying neighbouring buildings. Indubitably, investigation of this area should be done in order to select urban zone with a higher potential building damage. Results obtained clearly show, that tunnel depth and ground loss have a significant effect on the magnitude and pattern of surface settlement trough. On the other hand, higher values of ground loss lead to a significant increase of the extension of the critical area were buildings can be affected by structural damage induced by tunneling.

1. INTRODUCTION

Study of ground movements induced by tunnel construction in soft ground is an important issue for tunnel engineering, namely in congested urban area, where hundreds or thousands of buildings may be located along the tunnel alignment. Generally speaking, tunneling in soft soil generate stress relief in surrounding ground with stiffness reduction due to highly non-linear soil behaviour.

Consequently, tunnel excavation in soft ground produces systematically ground movements which propagate through the surrounding soil to the surface. Obviously, in urban environment, ground movements induced by tunneling may distort nearby buildings and cause serious damage to existing structures and utilities. Producing numerous problems, like construction delay and increase in project cost due to expensive remedial measures. Hence, it is important to have a deep understanding of ground movements produced by underground construction.

It is also very important to have a reasonable assessment of the extension of the area subjected to ground movements induced by tunneling in which the magnitude of settlements can be harmful to buildings adjacent to tunnel. Analysis of such area is very important because most of soil displacement occurs in this zone. Study of ground movements induced by tunnel works, is not straightforward and can be considered as a challenging issue in tunnel project, which is confirmed by many researchers like Mair et al 1998 [1] and Darabi et al 2012 [2].

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This complexity of ground movements investigation can be explained by the non-linear behaviour of soil and the three-dimensional nature of tunneling process involving significant disturbances of the surrounding ground, resulting in stress redistribution and strain changes. Which lead to an interaction phenomenon between tunnel and ground.

The literature review shows that research on ground movements produced by tunneling and study of the extension of area disturbed, has been performed by experts and scholars by means of various approaches. The largest part of published studies is based on, empirical or analytical approaches, reduced scale laboratory tests, numerical modeling and back analysis of in situ measurements collected during tunnel construction.

In practice, empirical or analytical methods are widely used in order to investigate ground movements produced by tunneling, which is confirmed by many author's like Fu et al 2014 [3]. Because numerical analyses namely three-dimensional modelling often requires important computational resources in terms of storage and time and required deep interpretation of results, this contrary to clarity of most classical approach's.

Nevertheless, the use of numerical modelling become more spread with the significant progress in computer codes and significant increase in computing ressources.

Several scholars have investigated extension of critical zone along tunnel alignment were nearby buildings can be affected by structural damage that can be arising from ground movements and developed various methods to assess the level of potential damage. This critical zone includes more specifically the extension of settlement trough induced by tunnel construction. Hence it is important to have a reliable assessment of the extension of this area prior to tunneling.

Camos et al 2016 [4], developed a model for probabilistic evaluation of building damage due to tunneling by using an empirical method to simulate settlement trough induced by tunnelling. The proposed model was applied to a real project. Results obtained show a good agreement between damage and settlement assessed and measurements made during the construction.

In the work of Fang et al 2016 [5], study of the ground surface settlement trough induced in real tunnel project is performed. The recorded surface settlements during construction and settlement troughs of typical sections are reported and illustrated in the work of Fang et al 2016 [5]. Also, the parameters that characterize the surface settlement troughs induced by tunneling, namely the maximum settlement, percentage of ground loss and trough width are presented and compared. In addition, results obtained show that parameters describing a surface settlement trough, such as the ground loss percentage and the trough width are significantly influenced by the ground reinforcement obtained by large grouting zone and steel pipes.

Son et al 2015 [6], conducted numerical parametric analysis, by using 2D numerical approach, in order to investigate tunneling induced ground movements in sandy soils and their effects on adjacent buildings. The study results proved that the building damage is strongly dependent on the tunnel- soil-structure interaction

Keshuan and Lieyun 2008 [7], investigated the tunnel–soil–building interaction by using a three-dimensional finite element model. This study provides a full analysis of the construction of shallow two tunnels in soft soil close to a five level building.Results obtained show that presence of the structure affects the soil surface settlement profile. Also, they observe sharp increases in soil settlement induced by tunneling in the vicinity of the foundations. In addition, Keshuan and Lieyun 2008 [7] found that during tunneling, longitudinal displacement of foundations increases when the tunnel face becomes close to the foundation section and then decreases when the tunnel face moves away from the foundation.

Vu et al 2015 [8], investigated the extent of the area impacted by tunnel works where building deformation exceed allowable settlement in order to calculate the limit distance from tunnel to existing foundations without serious damage to overlying buildings. In this manner safe and unsafe areas are presented. The main conclusion of his work, is that designers can determine the impact zone of shield tunneling on surface buildings or on deep foundations based on the allowable settlement of the building by using the approach followed in his paper for different combinations of tunnel diameter, cover and soil conditions.

Liu et al 2012 [9], conducted a parameter sensitivity analysis by using a numerical model. The accuracy of their numerical simulation is verified by comparing with in situ monitoring data. Results obtained indicates that building deformation and cracks are mainly caused by uneven settlement produced by tunneling. Dimmock and Mair 2008 [10] have investigated the response of two masonry buildings to tunnel excavation and they concluded that the structural behaviour of buildings in response to induced ground movements is closely related to the location of building regarding the profile of settlement trough.

Based on centrifuge modeling and field study, Farrell et al 2014 [11], have investigated the building response to tunnel construction. Obtained results in this study revealed that damage to buildings in the convex region of settlement trough (hogging mode) is significant, but also damage to buildings in the concave region of settlement trough (hogging mode) should be considered because building initiation of cracking in centrifuge model indicates that distortions in the concave region of settlement trough is also important. In addition, the study conducted by Farrell et al 2014 [11] indicate that the assessment of building damage based on the assumption that buildings distort fully flexibly conforming to the profile of settlements with ignoring the presence of the overlying structure, can be highly conservative.

Chen et al 2012 [12], investigated the interaction of twin tunnels in terms of settlement trough in surface. They studied the case of a real project by back analysis of settlement trough induced by twin tunnels based on empirical formula and by means of 2D finite element analysis. Results obtained , showed that ground surface settlement profile of twin tunnels could be conveniently and reliably estimated by using the empirical equation combined with the principle of superposition of the ground surface settlement trough.

Liao et al 2009 [13], conducted numerical analysis of typical cases of shield tunnel in shanghai soft soil by considering a tunnel excavated under old inclined building.

Settlement trough induced by tunnel works is studied for different value of ground loss and different configuration of grouting reinforcement and support pressure. Results obtained outlined the importance of each of this parameters in order to mitigate any potential negative impact on adjacent construction.

Boonyarak and Ng 2016 [14], performed centrifuge modeling combined with numerical back-analysis in order to sudy the influence zone of tunnel excavated underneath existing tunnel. Results obtained show that simplified influences zones proposed in the literature may not be able to capture the influence zone in the case studied.

In the work of Fragnoli et al 2015 [15], impact of twin tunneling in terms of settlement trough, in presence of a reinforced concrete building is analysed and discussed. The study refers to the case of a real tunnel project, excavated in coarse-grained materials using earth pressure balance machine. Comparison between numerical solutions and in situ measurements indicate that numerical model adopted by Fragnoli et al 2015 [15] provide reliable results of ground settlements above twin tunnels and lead to a comprehensive view of mechanisms of deformation affecting the building façades.

In this paper the extension of critical area in which surface settlement exceed the admissible value is investigated. Study of this area is very important because, in tunnel project, it should be considered, where the settlement produced by underground works are in allowable range or not. Special countermeasures can be implemented for such zone in order to reduce risk of building damage associated with tunneling project .

Assessment of building potential damage risk and the associated protective measures strategy should be based on the accurate assessment of critical area were buildings are located in order to satisfy requirements of structural integrity and hence to reach the goal of building security.

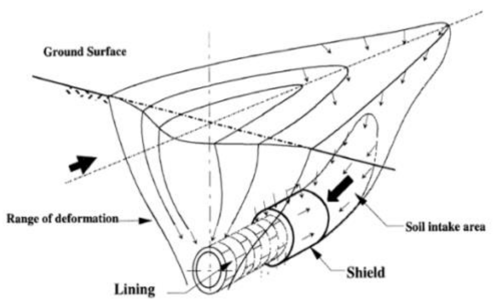

Fig. 1. Ground deformation induced by tunnelling after Suwansawat 2002 [16]

2. Presentation of the Problem Under Consideration

Tunnel studied have a circular section, with a diameter D = 8m. This tunnel is excavated in soft ground in urban area under overlying buildings and the objective is to analyse the extension of critical zone were buildings can be seriously impacted by tunnel ground movements.

The depth of tunnel is $Z_0 = 10m$ which is the vertical distance form tunnel centreline to the surface.

On the other hand, we choose a ground loss of $V_l = 3\%$ which is a value included in the range of empirical values presented later in this article.

It is interesting to note that the value adopted for tunnel depth and ground loss are typical values. Nevertheless, we use a parametric approach, in order to analyse the effect of variation of these parameters in term of magnitude of ground movements due to tunnel construction, and specifically, the surface settlement. The objective is to analyse the extension of critical zone and their relationship with some governing parameters.

3. Methodology

This paper focused on the critical area above tunnel alignment, were neighboring buildings can be affected by structural damage, by means of the Gaussian distribution function which is the most widely method used in practice engineering for studying vertical ground movements produced by tunnel excavation, combined with conventional building damage classification approach based on typical values of maximum settlement.

3.1 Study of vertical ground movements induced by tunnelling

Surface settlement curve arising from tunnelling is commonly termed as settlement trough.

It should be noted that since 1960, scholars have made a large amount of research about settlements produced by tunnel excavation. Nevertheless, the Gaussian distribution function is the most widely used method for assessment of vertical ground movements produced by tunneling in soft ground and is still commonly used in engineering practice. Which is confirmed by many researchers, like Jin et al 2018 [17], Liao et al 2009 [13] and Gong et al 2015 [18].

Gaussian distribution function is an empirical method developed by Peck 1969, in which the shape of surface settlement distribution is assumed to follow a gaussian distribution curve in the transverse direction. This method is based on the concept of ground loss.

The empirical formulation proposed by Peck 1969 is:

$$S(x) = S_{max} \exp(-x^2/(2*i^2)) \quad (1)$$

With

S(x): Settlement in surface
x: Horizontal distance from the tunnel centreline
Smax: Maximum settlement in surface
i: Trough width parameter

The trough width parameter "i" is an important factor which influence the extension of settlement curve in surface.

In the gaussian distribution function, the most significant parameter which need to be calculated is the ground loss V_l This is the key parameter for calculating settlement induced by tunnel construction. It's also a conventional indicator for the performance of tunnelling.

The ground loss V_l is obtained by dividing the volume of the settlement trough by the volume occupied by tunnel per linear meter which is the original cross section of tunnel.

$$V_l = Vs/Vt \quad (2)$$

Where

V_l: ground loss
Vs: Volume of settlement trough
Vt: Volume occupied by the tunnel

The volume of surface settlement trough can be obtained by integrating the equation above.

$$V_s = \int_{-\infty}^{+\infty} S(x)\,dx = \sqrt{2\pi}\, i\, S_{max} \quad (3)$$

Otherwise,

$$V_t = \pi\, D^2/4 \quad (4)$$

Hence

$$V_l = \sqrt{\frac{32}{\pi}\frac{i\, S_{max}}{D^2}} \quad (5)$$

In practice, ground loss V_l is quantified by empirical method's.

Ground loss V_l is not a constant, because it depends on several factors like geotechnical conditions and tunnelling method used.A substantial number of research works, have investigated the ground loss associated with tunnel excavation. In this sense, several researchers have proposed practical values of variation of ground loss based on empiricism gained from tunnelling works. Typical values of ground loss proposed by researchers are listed in table below.

Table 1. Values of ground loss

Author's	Range of variation of ground loss	Conditions
Attewell 1977	$1\% \le V_l \le 5\%$	--
Chapman et al 2004	$0.5\% \le V_l \le 2\%$	Most tunnelling operations
O'Reilly and New 1982	$0.5\% \le V_l \le 3\%$	--
Burd et al 2000	$V_l = 2\%$	Typical of real tunnelling operations
Augarde 1997	$1\% \le V_l \le 3\%$	Tunnelling in clay

Another important parameter in the gaussian distribution function which need to be assessed is the trough width parameter "i"

The trough width parameter has a linear correlation with tunnel depth. In practice, this parameter is commonly calculated by means of the formula proposed by O'Reilly and New 1982 :

$$i = k * Z_0 \quad (6)$$

With

Z_0: Depth of tunnel axis

k : Coefficient depending on the nature of ground. O'Reilly and New 1982 reported that k=0.5 is an appropriate value for clay.

3.2 *Building damage classification*

Rankin 1988, proposed a simplified building damage classification with typical values of maximum slope and maximum settlement of building. Four categories of building damage ranging from 0 (negligible) to 4 (High) are used to define possible degree of damage.

Table 2. Building damage classification after Rankin 1988

Risk category	Maximum slope	Maximum settlement(mm)	Risk description
1	$< 1/500$	< 10	Negligible
2	$1/500 \mapsto 1/200$	$10 \mapsto 50$	slight
3	$1/200 \mapsto 1/50$	$50 \mapsto 75$	Moderate
4	$> 1/50$	> 75	High

4. Results and Discussions

4.1 *Effect of tunnel depth on surface settlement trough*

Settlement trough obtained for different values of tunnel depth Z_0 , by using the method displayed previously, is reported in the graph below. The ground loss is maintained at V_l=3%.

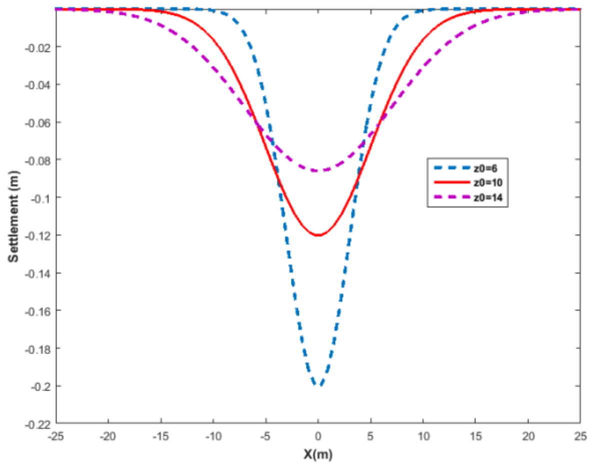

Fig. 2. Settlement trough obtained for different value of tunnel depth

We can see from the figure above, that the settlement profile is symmetrical and the symmetry center is on the tunnel axis. In addition, the maximum settlement occurs above the tunnel centreline. Furthermore, results obtained, show that the tunnel depth has a significant effect on the profile of settlement trough. The increase of tunnel depth induces a substantial decrease of the magnitude of surface settlement. When tunnel depth increases from 6 to 14m, the maximum settlement decreases by about 150 %. In the contrary, the increase of tunnel depth produces an increase of the width of settlement curve.

Moreover, a significant difference, can be observed between the settlement profiles in terms of shape of settlement trough when the depth of tunnel increase. When tunnel depth is sufficiently low which is the case of shallow tunnels, we can see that the settlement trough is significantly narrow but the amplitude of settlement is high. Nevertheless, the increase of tunnel depth, induce a flat shape of settlement trough with a low value of settlement amplitude, which is the case of deep tunnels. In other words, the transverse spread of settlement trough is closely related to tunnel depth.

4.2 Effect of ground loss on surface settlement trough

Settlement trough obtained for different values of ground loss, by using the Gaussian distribution curve, is reported in the graph below. The tunnel has a circular section, with a diameter D = 8m. Tunnel depth is Z_0=10m from surface to tunnel axis.

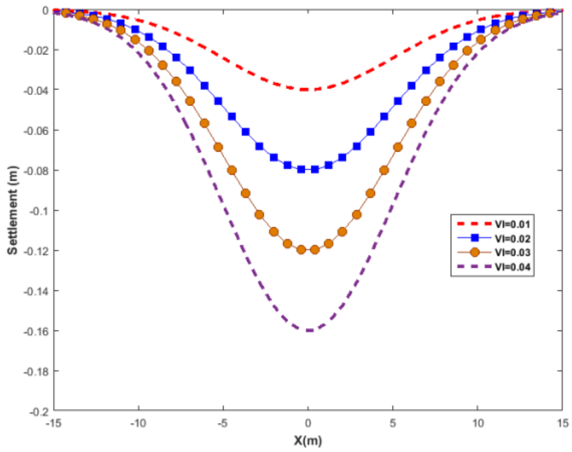

Fig. 3. Settlement trough obtained for different values of ground loss

Results reported in the figure above, clearly show that the ground loss has an important influence on the magnitude and the pattern of surface settlement distribution. Increase of ground loss induce an important increase of the magnitude of settlement and also modify the pattern of settlement trough.

4.3 Characterization of critical zone

The typical value of 50mm is taken as the allowable settlement. Indeed, the threshold in terms of settlement of the second risk category is 50mm. Below 50mm as settlement, the building damage risk can be considered as slight with superficial disorder without any structural effect or negligible effect. However, the risk become moderate with a settlement larger than 50mm.

Hence the choice of the typical value of 50mm is justified for the critical area. X_{limit} define the horizontal distance from tunnel axis to the boundary of critical area , which means that buildings located inside this area can be seriously affected by tunnel works. On the other hand, buildings located at a distance more than X_{limit} from tunnel centreline, can suffered only from slight or negligible superficial damage without any structural effect, like hairline cracks or fine cracks in walls which can be easily treated.

4.4 Effect of ground loss on the width of critical zone in surface

The figure below displays the relationships between the extension of critical zone l=2*X_{limit}, were surface settlement can exceed the allowable settlement (S_{adm}=50mm) and the ground loss. Tunnel depth is Z_0= 10m from surface to tunnel axis.

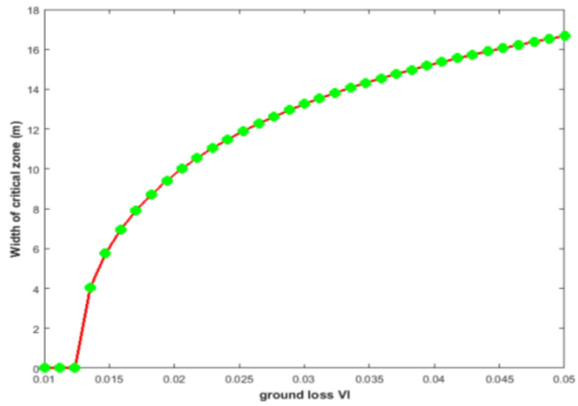

Fig. 4. Width of critical zone for different value of ground loss

As seen in the figure above, the width of critical zone increases by increasing the value of volume loss. That means that ground loss should be reduced and maintained at low level in order to minimize the area of critical zone. Reduction of volume loss can be done by drastic control of quality of underground works namely by using a sophisticated tunnel boring machine, with face support combined by injection of grout which is a visco-plastic material, in the gap between concrete lining and the excavated soil. In practice sophisticated tunnelling technology with support, reduce significantly ground disturbance and consequently provide good results in terms of ground loss.

4.5 Relationship between tunnel depth and the extension of critical area

The figure below shows the relationship between tunnel depth "Z_0" and "X_{limit}" which define the horizontal distance from tunnel axis to the boundary of critical area.

We have considered the normalized ratio X_{limit}/D and Z_0/D, in order to analyse respectively the normalized horizontal distance from tunnel axis to the boundary of critical area and the normalized depth of tunnel. The value of ground loss considered is V_l=0.03 and the admissible settlement is S_{adm}=50mm.

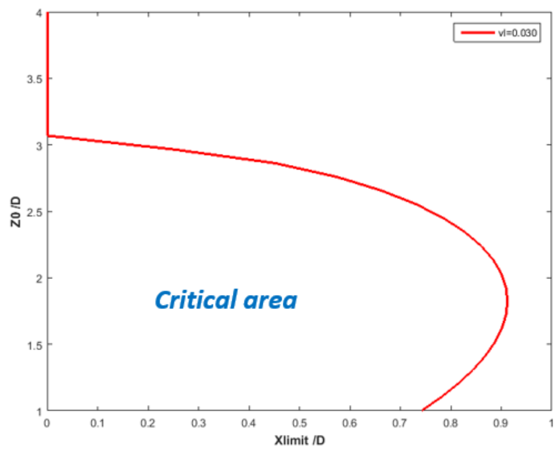

Fig. 5. Relationships between tunnel depth and the extension of critical area

In the figure above, the area inside curve represents the critical zone in which the typical value of admissible settlement fixed at 50mm is surpassed. This value, is the limit between slight and moderate risk damage, according to classification of risk damage aforementioned.

In this zone, potential damage can arise for every structure located in this area, with a high or moderate risk level combined with potential structural damage to buildings .

We can see that for the values of X_{limit}/D and Z_0/D ratios inside the critical zone, the value of settlement exceed the allowable settlement fixed at 50mm. In the borderline of this area we have the surface settlement which is equal to the admissible settlement S_{adm}=50mm. In the outside of this area the settlement is less that the admissible value and consequently risk damage is slight or negligible.

More specifically , with values of X_{limit}/D ratio between 0,742 and 0,912 , for each value of X_{limit} include in this interval, there is two values of the tunnel depth for which the surface settlement is equal to the admissible settlement.

Otherwise, in the case studied where v_l=0.03, the figure above show that with Z_0/D ratio larger than 3,1, the surface settlement is less than the admissible settlement regardless the value of the X_{limit}/D ratio. This means that, when constructing tunnel with a depth slightly more than 3 D, in the case where V_l=0.03, there is no serious risk damage to overlying buildings.

On the other hand, the obtained results show that for X_{limit}/D value larger than 0,92 or X_{limit} larger than 7,36m from the tunnel centreline, the surface settlement is less than the admissible settlement, which means that buildings located at a distance more than 7,36 m from tunnel centreline can suffered only from slight or negligible superficial damage without any structural effect, like hairline cracks or fine cracks in walls which can be easily treated.

4.6 Effect of variation of ground loss on the relationship between tunnel depth and the extension of critical area

The figure below shows the relationship between the normalised horizontal distance from tunnel axis to the boundary of critical area X_{limit}/D and the normalised depth of tunnel Z_0/D, under various value of ground loss V_l .

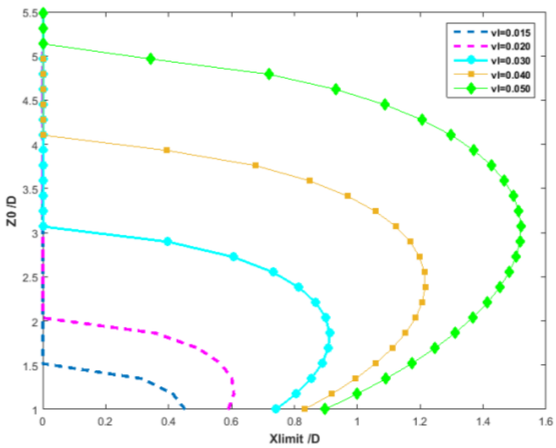

Fig. 6. Relationship between Xlimit/D and Z0/D for different value of ground loss

Results obtained above, illustrate the critical zone representing the area inside the curve, in which the settlement is larger than the admissible settlement , it can be observed that the higher value of ground loss leads to a significant increase of the extension of the critical area were buildings can be affected by structural damage induced by tunnel construction.

It should be clarified that the ground in the critical area is seriously disturbed by tunnel excavation which manifested by an important value of settlement magnitude which can distort overlying buildings located in this area.

5. CONCLUSION

Tunnel project involves several kinds of risks related to ground movements associated with tunnel excavation in soft ground. Impact of ground movements and particularly surface settlement should be carefully investigated during design and construction of tunnel. In particular, the detrimental effect of settlement on buildings should be deeply investigated in order to avoid any structural damage.

In this paper, ground settlement trough induced by tunnel excavation in soft ground is investigated by means of the gaussian distribution function. We have studied the effect of ground loss and tunnel depth on surface settlement trough.

In this research we have studied deeply the extension of the critical area were buildings can be seriously impacted by tunnel ground movements and we have analyse the effect of ground loss on the width of critical zone in surface. Moreover, the relationship between tunnel depth and the extension of critical area is analysed. In addition, effect of variation of ground loss on the relationship between tunnel depth and the extension of critical area is investigated.

Results obtained clearly show, that tunnel depth and ground loss has an important influence on the magnitude and pattern of surface settlement distribution. In addition, it can be observed that higher values of ground loss lead to a significant increase of the extension of the critical area were buildings can be affected by structural damage induced by tunnel construction.

That means that ground loss should be reduced and maintained at low level in order to minimize the area of critical zone. On the other hand for the typical case studied were ground loss is equal to V_l=0.03, results obtained show that: For values of X_{limit}/D ratio between 0,742 and 0,912 , for each value of X_{limit} include in this interval, there is two values of the tunnel depth for which the surface settlement is equal to the admissible settlement.

Furthermore, when constructing tunnel with a depth slightly more than 3 D, in the case where V_l=0.03, there is no serious risk damage to overlying buildings. Otherwise, the obtained results show that for X_{limit}/D value larger than 0,92 , the surface settlement is less than the admissible settlement .

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