Response of Twin Transportation Tunnel in Earthquake Loading: 
A Review

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Abstract: Tunnels are a major underground structure used for transporting passengers, water, wastewater, etc. Design of a tunnel/twin tunnel requires fixing the spacing between tunnels, assessment of hazards to surface structure due to tunnelling and protection measures, etc. Experimental, numerical, analytical methods or a combination of the above techniques are used to design and investigate the stability under static and dynamic conditions. Ground settlement due to tunnel construction, the spacing between the tunnels, the tunnel response during earthquake loading, influence of alignment, etc., have been reviewed and summarized from the past published literature. A summary of the different design criteria for twin tunnels is reviewed and presented here. The present paper will be helpful for engineers and researchers working in this area.

Keywords: Earthquake, Dynamic Load, Twin Tunnel, Ground Settlement.

1. Introduction

The creation of urban towns includes the usage of underground areas for the building of a roads and services for transport. Geotechnical and underground conditions in some cities require the creation of new tunnels close to the current ones. In another situations, twin-tunnel approach has important benefits, such as minimizing both the width of the tunnel and the displacement of the soil arising from the building of tunnel \cite{1}. Growing demand for infrastructure has resulted in increased exposure in urbanized areas to shallow soft ground tunnelling techniques. Control of surface settlement that are observed earlier and later excavation, which can cause disturbance to surface structures, is especially important in metro tunnel excavations. Metro tunnels usually excavated as twin tunnel, unlike motorways, sewage and other infrastructure tunnels, besides must have wider diameter. Metro tunnels are small in depth as well. Metro tunnels have usually been built on weak soil or weak rock in cities due to their shallow depth.

Twin tunnel construction can produce ground motions that can cause disturbance to existing surface and on subsurface structures. Various experts have used slurry balance machine and the Earth pressure balance machine (EPBM) to solve this settlement problem. In such excavations, especially in twin tunnels, calculating the maximum surface displacement, regulating the interaction of transverse surface settlement and shaping the settlement curve are the main challenges for builders. Incorrect calculation of these parameters will leading to major problem in the tunnel and surrounding constructions \cite{2}. The impact of seismic load on tunnels is much too important. Extensive research on the impacts of earthquakes on tunnel indicate that wide tunnel deformations and axial stress on the tunnel lining is caused by earthquakes. In laboratories, numerous model is dynamically loaded. Then, using numerical tools, the similar conditions are analysed. Similar findings have been obtained in both cases. Different criteria are important in the assessment of dynamically loaded tunnels and widespread research work is done in this respects. However, variations in soil resistance parameter and changes in soils cohesion are not adequately considered in the above-mentioned study using traditional methods. The impact of parameters, soils resistance on force applied to linings is important. One of the maximum productive soil parameter is soil cohesion. As increased soils resistance does not permanently contribute to a decline in the strength of structure that are in contact with them. The impact of seismic loading at tunnels is much important.

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However, single tube tunnels and twin tunnels had been studied by researchers under different loading conditions [3-9]. In addition, behaviour of jointed rock mass also plays significant role in geotechnical structures [10-13]. Extensive research on the impacts of earthquakes on tunnels suggests that earthquakes cause substantial deformation of the tunnels and axial stress on lining of the tunnel. In laboratories, numerous model is dynamically loaded. Then, using numerical tools, the similar conditions are analysed. Different findings were obtained in both cases. Different criteria are important in the assessment of dynamically loaded tunnels and wide research is completed in this respect. However, variations in soils resistance parameters and variations in soils cohesion are not adequately calculated in the above-mentioned study using traditional methods. The impact of parameters of soils resistance on forces applied to lining is important[14-17]. One of most productive soils parameters is soil cohesion. Increment in soils resistance does not permanently contribute to decrease in the strength of the structures that are in interaction with them [18]. Underground structures are stronger against dynamic waves than surface structures, since surface structures is only connected from lower surface to the ground and freely vibrate; however underground structure is entirely connected to the external atmosphere and are therefore more vibration-resistant. There are records, however, damage to these structures because of dynamic waves. That means that underground structure is not entirely resistant to dynamic waves and susceptible to damage. Therefore, the relative strength of these structures against earthquake does not assurance that dynamic loads, especially earthquakes, are adequately resistant.

Accordingly, essential and ongoing research on waves propagation in soil and rock is crucial. In shallow and soft environments, most urban underground structures are built and are therefore vulnerable to a seismic disturbance. Depending it on their application, such mechanisms are of considerable value in terms of a long-term protections. Their seismic behaviour should be estimated when the construction location of large underground structure such as the public transit tunnels is very soft and loose. Many studies have focused on impact of single tunnels excavation in terms of subsurface and surface movements in recent decades. On the other hand, many metro-line plans round the world, the case of twin tunnels is now very popular because twin tunnelling is especially preferred when constructing underground transit networks worldwide. One of most interesting problems in the geotechnical engineering is understanding the behaviour of an underground structure through earthquake events. While tunnels were usually better installed during earthquakes than above ground structures. The effects of earthquakes on the underground structures result in two different groups: (1) ground shaking, (2) a ground failures such as a liquefaction, displacement of faults and instability of slopes. Land shaking refers to the soil vibration due to seismic waves that spread through the crust of the earth. [19]

2. Tunnelling Methods

![Diagram of Tunnelling Methods](image_url)

**Fig. 1. Various methods of tunnel construction**

*Types of tunnel construction method: Earth Pressure Balance, Variable Density Tunnel Boring Machine, Tunnel Boring Machine, New Austrian Tunnelling Method [5]*
The construction of tunnels requires appropriate technology and techniques to be applied. Because of the variable ground condition, the selection of the suitable method for tunnel excavation is mostly dependent on field experiences rather than the estimates of the theoretical expertise, and yet there is no other separate or proper law for it. The choice of method for tunnel construction depends on many factors, such as the depth of the tunnel, the form of tunnels, the length of tunnels, the diameter of tunnels, groundwater levels, tunnel use, logistics supporting tunnel excavation and adequate risk management. Tunnels size, the underground hydrology, regional geology, structural geology and surrounding material properties with its geotechnical characteristics, a weak zone characteristics and induced stresses, are the most powerful factors that play a significant role in policymaking for the appropriate selection of the excavation process [20].

3. Relative position and diameter

Since cities are highly concentrated with high structures, settlement at the base of the structures would be caused by laterally dispersed loads. Both relative location of the tunnels and construction method can influence the soil displacement and internal forces at linings for a specific orientation of the tunnels. The supreme for vertical aligned tunnels, soil settlement is obtained, whereas horizontal aligned tunnels create the lowest settlements and with a greater lateral allowance of the settlement. In case of bored tunnels, a variety of variables such as tunnel size, in-situ stress field and continuum properties rule the magnitude of the secondary stress produced after excavation (physical, elastic and strength). There are many methods available in the literature for the study of induced stress and displacement around tunnels. The implementation and feasibility of adequate research can be evaluated by keeping the process of construction and material actions under various stress conditions in mind. Tunnelling-induced movements, such as land settlements and lateral movements, are critical for the protection of established structure in highly developed urban environments.

![Horizontal Alignment](image1)
![Inclined Alignment](image2)
![Vertical Alignment](image3)

Fig2. Different types of Tunnel Alignment

Tunnels are also designed for metro rail transportation. These are built at near intervals and at shallow depths. It is therefore important to find the possible settlement that may occur due to tunnelling. If the expected settlement reaches the allowable limits, necessary steps need to be implemented. It can be noted that both the tunnel design and the construction process have a major impact on the settling of the surface soil and internal forces of tunnels. The bending moment of tunnel is mildly influenced by design direction of the tunnels. For vertical aligned tunnels, the highest soil settlement is obtained, whereas horizontal aligned create the lowest settlements with greater lateral allowance of the settlement. Lower tunnel construction initially leads to more soil settlement than that caused when upper tunnel was first built[21].

4. Ground Surface Settlement

Tunnels in urban environments are often located in soil or soft rock at small depths below densely populated areas, and their construction may affect established surface structures. Reliable prediction and control of soil surface settlements are therefore essential tasks for the design of urban tunnels. Any subsurface development can produce ground displacement that have potential to cause harm the existing surface and underground construction, such as land settlements and lateral movements[22-26]. The need for precise forecasts of tunnelling-induced soil settlements was forced by urbanisation and congested cities. For surface settlement profiles induced by a single tunnel, the Gauss curve is common. Yet, either subsurface movement or stress distribution cannot be provided by this curve. Generally speaking, rapid transport networks consist of a pair of close-by tunnels, also known as twin-tunnel structures. For surface settlement profiles induced by a single tunnel, the Gauss curve is common. Yet, either subsurface movement or stress distribution cannot be provided by this curve. Generally speaking, rapid transport networks consist of a pair of close-by tunnels, also known as twin-tunnel structures. Single-tunnelling
affected surface, subsurface settlement is well defined by the Gaussian distributions, but due to the second tunnel construction alone, twin-tunnelling estimates can be enhanced by changing the settlements. It is possible to predict ground settlements caused due to construction of second tunnel by using equations given by Peck, O'Reilly & Fresh, and Mair et al., along with various modifications. The distribution of the surface, subsurface settlements along the current tunnels was found to be broader than for single tunnels[27-32]. Due to the presence of the first tunnel, the degree of volume loss caused by the newly formed tunnel system is increased. Larger distances between the tunnels could reduce this effect. For expecting surface settlements above the twin-tunnels structure, the Superposition Method is a simplified technique. A tunnelling-produced ground settlement curve placed at over the center-line to each tunnels is obtained according to this simplified procedure, ignoring any effect from the other tunnel. The total settlement is defined by the summation of these two overlapping curves.

Several methods, including observational methods derived by field observations, centrifuge modelling, computational and analytical methods, may be used to predict tunnelling-produced ground movements at the excavation of twin tunnels. A distribution of ground motions with certain coefficients is assumed by the empirical method. Via fitting field or centrifuge measurements, these coefficients are calculated. For twin-tunnelling-derived surface, subsurface settlements, analytical expressions are depend on simplified methods which use the concept superposition of the two individual ground settlement curves induced by tunnelling. This strategy disregards any relationship between the two tubes that are closely spaced. The computational simulation of shallow tunnels has made considerable strides in recent years. As many variables as possible should be used in computational and analytical methods, may be used to predict tunnelling-produced ground movements at the tunnel, the degree of volume loss caused by the newly formed tunnel system is increased. Larger distances between the tunnels could reduce this effect. For expecting surface settlements above the twin-tunnels structure, the Superposition Method is a simplified technique. A tunnelling-produced ground settlement curve placed at over the center-line to each tunnels is obtained according to this simplified procedure, ignoring any effect from the other tunnel. The total settlement is defined by the summation of these two overlapping curves.

5. Stress and Deformation

The building of the subway transport systems, as metro tunnel, is important structure. Although they have various advantages, tunnels construction can cause undesired impact on existing structure by ground deformation, particularly through weak materials. Secure tunnels design and the construction therefore involve stability, deformation of the surface and effective support; therefore, for tunnel projects, the calculation of soil settlements, their impact on structures at above the tunnel is important[34–35]. Deformation may be managed by means of additional linings system, such as jet grouted columns, a ground freezing and pipe jacking, when the strong support at the tunnel face needed, pre-support, a pre-confinement, an auxiliary method and a pre-improvement are additional primary pre-support means uses in tunnelling. The twin tunnel-induced surface settlement was less influenced by the friction angle and cohesion parameters. The modulus of deformation and Poisson's rock mass ratio, however, resulted in the greatest changes in settlement values, as settlements is primarily controlled by the stress and strain states of tunnel's adjacent medium[36].

Due to the shallow-buried twin tunnel design, numerical approach, empirical formula and theoretical modelling are widely used for the prediction of ground responses (stresses and displacement). In comprehensive tunnel design, the numerical approach is commonly used, taking into account complex geological situations, as well as the relationships between tunnel and the existing structures. In the region between of two tunnel, and between the tunnels and ground surface, influences of twin tunnels interaction at displacements and stresses widely appeared. The largest displacement at tunnels boundaries and largest surface settlements, were achieved whenever the tunnels arrangement angle alpha was 30 ° when surcharge load was exerted on the ground surface immediately above tunnel 1[37]. With an increase the stiffness of lining, the maximum and minimum principal stresses of tunnels increased, but the improvements in maximum acceleration and displacement were not apparent[38]. Stress distribution is altered after excavation in the underground space, and induced stresses are produced. Shear stress is, of course, zero at the excavation boundary and the tangential stress rises[39].

6. Stability

One big issue that engineers are concerned with is their stability in design and building of underground structure. Since adjacent soil/rock mass mechanical activity has not up till now been completely understood, failure accidents often occur, producing significant loss of human life and property. Thus, various researches on stability of these underground structures is important and urgent[40]. For the art of tunnelling, assessing stability of these tunnels is a leading activity. A number of experiments, ranging from theoretical approaches to numerical simulations, has been performed to test the stability of single tunnels. Twin tunnels are often encountered in construction engineering, since development of twin tunnel is typically more cost-effective alternative than single
larger diameter tunnel. The stability of the dual tunnels must be understood because, as contrasting to a single tunnel, it is greatly influenced by the centre-to-center gap [41]. The value of maintaining stability during tunnel driving and limiting deformation on adjacent structures is well acknowledged in tunnelling. In their opinion, under undrained conditions, the volume of the settling trough caused by its excavation should equal to volume of soil loss. These empirical techniques of calculation, however limited in case of single tunnels.

The assessment and monitoring of ground movement, deformation and stability of the excavation front, and loads and stresses in the tunnel support system play a major role in the tunnel design and construction [39]. As with reduction in spacing(S) among tunnels, stability number (N) continuously decline. As with function of H/D (H is tunnel cover), S/D (D is each tunnel diameter), m and internal friction angle, the variation of N was defined. With a reduction in spacing between the two tunnels, the stability number decreases considerably. The stability number is also increases continuously with an increase in H/D, and inner friction angle values [42]. Generally, with increasing S/D, H/D and 9, stability number increases and decreases as increase in the γD/c value (c is soil cohesion) [41]. Under static loads, the tunnel roof varies in displacement and velocity more than the rest of the tunnel. The tunnels are, as a result, stable under static loading. A sinusoidal wave applied to lower boundary of model in order to apply dynamic load, which was more than other tunnel points later applying a dynamic loading, displacement and with velocity variations in the tunnel floor. As a consequence, under dynamic load, the tunnels are unstable [39].

7. Seismic Behaviour

In shallow and soft environments, most cities underground structure are built, thus vulnerable to seismic disturbances. Such systems are of high significance according to long-term protection, depending on their use. Their seismic behaviour should be estimated when the development site of underground structures as public transit tunnels is very soft and loose. The effects of seismic load on underground structure result in two different groups: (i) the ground shaking and (ii) the ground failures as liquefaction, displacement of faults or instability of slopes. Land shaking refers to the soil vibration due to seismic waves that spread through the crust of the earth. Seismic waves are two types (a) Body waves pass inside the substance of the Earth (S and P waves), (b) Surface waves move around surface of the Earth (Love or Rayleigh waves) [19]. Seismic loading on underground structure is too much important. For soil masses with cavities, a true dynamic analysis is needed rather than relying on equivalent dynamic procedures. It's possible that earthquake energies would be attenuated near pillars, particularly in shallow tunnels. In terms of moments and thrusts, flexible joints work better under earthquake loads. However, thrust variations are minor, while moment variations can be safely managed by designing against contraction moments[43]. During the damage caused by the earthquake, two types of tunnel lining failure were identified: the first is based on the value of Peak Ground Acceleration (PGA), and the other is related to the displacement of the soil environment around the tunnels. Ground deformability is important for tunnel lining stability, particularly in seismic loads[44]. The stress in tunnel lining is evenly distributed in the cross-section of the tunnel lining if the tunnel lining has a circular cross-section. Under the impact of earthquakes, the stress value occurring in the tunnel lining in cases at which tunnel lining has a circular cross-section is less than the stress value occurring in the tunnel lining in cases at which tunnel lining has a rectangular cross-section[45].

Extensive research on impact of earthquakes on the tunnels suggest that seismic load cause substantial oval deformation of the tunnel and axial stress on the lining of the tunnel. One of most productive soils parameter is soil cohesion. At increasing soil resistance does not permanently contribute to a decline in the strength of the structures that are in contact with them. As example, friction angle can specify which increases and leading to increase in the force existing in the tunnel lining. At increased forces are causing faster tunnels deterioration in tunnel linings. The design of tunnels linings structurally affected by shear forces, axial forces and bending time, and these forces can be greatly affected by the amount of soil cohesion. Improvement quickly raises the cohesion of soils. The addition of cementing materials to the soil allows this improved cohesiveness [18]. Under static and dynamic loads, the twin tunnels are very unstable and require a support scheme. Stress distribution is altered after excavation in the underground space, and induced stresses are produced. Shear stress, however, is zero at the excavation boundary and the tangential stress increases. Unbalanced force increases after boring tunnels and applying dynamic and static loads, but the increment in disturbed forces is more under dynamic loads [19]. Seismic study of vertically oriented twin tunnels: Vertical stresses increase to a pillar width of 0.5D at the critical points and the liner pressures in both tunnels at the time of earthquake. However, with increasing pillar distance, this rise in the vertical stress and liner force shows a declining pattern. Vertical stresses rise during the earthquake at the
critical points in both tunnels and earthquake creates an increment in vertical stress at both tunnels with increasing pillar distance [46].

8. Sustainability in Tunnels

Sustainability is the roadmap for several countries and agencies, incorporating sustainability properly into large infrastructure projects, such as tunnels, is still a significant challenge. This is noteworthy, as the design, operation of all these civil engineering infrastructures are generally acknowledged to have a significant effect on the environmental, social and economical sustainability. In general, the above conclusion shows to lead a lack of visualization for tunnels in terms of sustainability. The focus of sustainable construction has long been on buildings, and infrastructure and civil works have received far less attention. As unique type of civil engineering infrastructure, the tunnel industry particular have been slow to accept this challenge, there are not various well known projects of tunnels that are sustainable. This gives an exploratory character to the adoption of sustainability with regard to tunnel projects [47].

Table 1. Sustainability aspect of materials and resources

| Sustainability aspects                                      | Definition                                                                 |
|------------------------------------------------------------|---------------------------------------------------------------------------|
| Utilization of resources, materials                        | Decreasing the quantity of used resources, materials.                      |
| Origin of resources, materials and environmental impact    | Option of (building and sustaining) materials along consideration of low environmental effects. |
| Re-use and utilization of recycled materials               | Maximize re-use for components, utilization of recycled materials, aggregates. |
| Waste on constructions                                    | Minimization (construction) waste and effect on environment                |

9. Conclusion

In this era of advanced computer technology, if used and treated correctly, numerical method can be very useful over other methods. In order to achieve precise results of tunnelling-induced settlements, the numerical approach needs better user expertise, information and skills in terms of modelling and analysis. 3D numerical analysis has more benefits and is recommended than 2D analysis. However, if suitable methods and ground models are used, 2D analysis may also provide better results. Since most research on soft-ground tunnelling have been carried out, more detailed studies are required for tunnelling in various soil conditions, such as rocky soil and mixed-faced soil. Twin tunnel diameter varied from 2 m to 10 m and its spacing varies from the 0.2 to 2 times of the diameter. It was derived that the minimum spacing of tunnel should be 0.8 times of tunnel diameter. It was observed that smaller diameter tunnels impact on only surrounding field but larger diameter tunnels impact surrounding fields as well as faraway fields [48].

The decreasing impact of the pre-support has not been included in previous researches concerning the valuation of magnitude of maximum surface displacements induced due to NATM-twin tunnelling. In addition, most of the proven empirical calculations were derived by utilizing data from twin tunnels passing in the artificial soil [36]. With respect to safety in tunnel design, the pressure distribution across tunnels played a serious role. To measure pressures around tunnels, numerical simulations, in situ monitoring studies and experimental tests have been created. The demand of twin-tunnel has been rising compared to the single tunnels. Therefore, this motivates more attention to design of the multi-layered strata twin-tunnels. For measure the pressure distribution surrounding the twin tunnel crossing layered strata, we can see some theoretical approach [49].

The importance of these structures makes their earthquake vulnerability is very complex issue. A major earthquake responsible for the potential harm of human life and it could also destroy a lot of other infrastructure. Vertical stresses rise during the earthquake at the critical points in both tunnels and earthquake creates an increment in vertical stress at both the tunnels with increasing pillar distance [46]. The role of twin tunnels spacing and diameter of tunnel in its stability it was investigated using the method of finite elements, Not a lot of analysis twin tunnel
Spacing has been performed in hard rock. Various research available single tunnels in layered soil and lack of twin tunnels in layered soils. Safety and stability aspect of metro tunnels during earthquake is also a serious concern.

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