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Static and seismic assessment of an existing tunnel due to a new tunnel placed vertically below at different spacing

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Abstract - *The significance of tunnel construction has elevated manifold owing to its diverse applications in contemporary transportation and communication infrastructures. Nonetheless, the seismic susceptibility of these underground structures is of utmost concern due to their vulnerability to different forms of damage. Consequently, this article undertakes a static and seismic analysis of an existing tunnel, both in the absence and presence of an additional new tunnel of same diameter, positioned vertically below the existing tunnel at different spacing. A 2D plain strain soil-tunnel model is created using Finite element analysis software GTS NX Midas. The characteristics of the soil are similar to the alluvial silts found in Delhi and the earthquake selected for seismic analysis is the Loma Preita earthquake. Response-spectra compatible earthquake data is produced using SeismoMatch software. The response parameters obtained from the results are in the form of forces generated in the existing tunnel lining such as axial force, bending moment, shear force, and contours depicting ground displacement. From static analysis, it is observed that due to a new tunnel, the lining forces in the existing tunnel decrease, whereas with increase in distance between the two tunnels, the existing tunnel of the twin tunnel system behaves similar to the single tunnel. However, during seismic analysis, there is negligible difference between the single tunnel and the existing tunnel of the twin tunnel system after a certain distance. Therefore, it can be understood that the seismic stability of the existing tunnel is independent of the vertical spacing of the new tunnel.*

Key Words: **plane strain, twin tunnel, alluvial silts, static and seismic analysis.**

1. INTRODUCTION

The beginning of underground tunnels traces back to 2200 B.C. Since their inception, these tunnels have served different purposes in transportation and communication. The ever increasing urbanization has led to a scarcity of available aboveground space for further expansion of communication networks and utility services. Consequently, in the contemporary era, there is a growing demand for underground structures, particularly tunnels, to cater to various developmental requirements. Over the years, there has been a prevailing assumption that the underground structures offer greater seismic safety compared to their aboveground counterparts, attributed to the inherent restraint provided by the surrounding soil or rock. However, a multitude of incidents has demonstrated significant tunnel damage resulting from seismic events. Hashash [1] has cited several case studies which highlight the need for enhanced seismic design and mitigation strategies to bolster the structural integrity of tunnels in earthquake-prone regions.

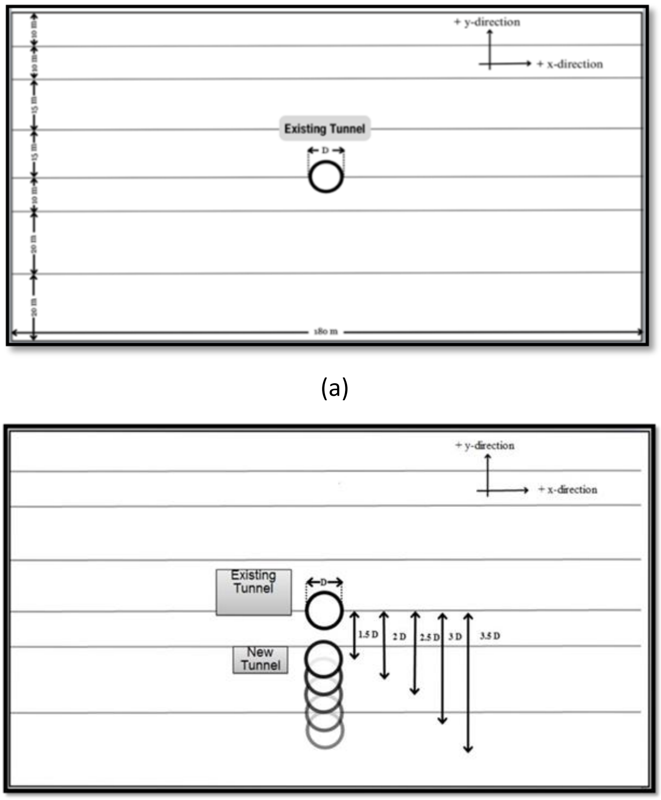
Seismic waves can induce significant structural impacts beyond those anticipated for an isolated tunnel due to a new adjacent opening. Research has been performed to anticipate the induced stresses in pre-existing tunnel structures during seismic events, especially accounting for the excavation of a neighbouring tunnel [2]. However, simpler approaches by Corigliano [3] have been found to yield good results for seismic analysis of deep tunnels, but an extensive assessment of the dynamic growth of internal stresses on the lining is essential for stable design in seismically active locations. The study looks at a variety of analytical methodologies, including simple procedures and advanced numerical simulations, to estimate the seismic stress increment and the reliability of pseudo-static solutions Also, Bobet performed a research [4] that introduced new mathematical methodologies for evaluating the effect of pore water pressure on tunnel stability under static and seismic loading. The research investigates the drainage conditions at the ground-liner interface, as well as the impact of groundwater pressure on ground and support reactions. Similarly, the study carried out in [5] focuses on seismic analysis of deep twin tunnels in Indian cities such as Delhi, taking into account specific soil properties and using a pseudo-static approach. The study quantifies the additional moments, thrusts, shear, and surface displacements caused by earthquake stresses on the tunnel liner, highlighting the need of including seismic loading into twin tunnel designs. Wang [6] determined the maximum bending moments using the full-slip closed form solution and compared to those obtained by no-slip finite difference analysis. The full-slip assumption resulted in higher bending moments than the no-slip assumption. The full-slip assumption resulted in somewhat more ovaling (distortion) of the lining, while the differences were insignificant. There is another research [7] which focuses on the effect of constructing an additional tunnel, either horizontally or vertically aligned, on the response of the existing tunnel. The analysis is conducted in both static and seismic conditions by altering the pillar width between the tunnels. The study shows that following an earthquake, vertical stresses at critical areas and forces in the tunnel lining of horizontally aligned twin tunnels gradually increase for a pillar width equal to half the tunnel's diameter. The vertical strains and forces in the first tunnel's lining increase with respect to pillar width. Bazaz and Besharat [8] investigated the seismic study of shallow tunnels in a soil medium, with particular focus on the behaviour of circular cross-section tunnels during operation, by comparing numerical findings with analytical responses provided by Penizen and Wang. The results show a relative error in the analytical approaches, and increasing soil stiffness reduces the resulting circular stress in the lining. This is also proved in another study [9] which states that the axial force in the tunnel lining decreases significantly as soil cementation improves. Also, a decrease in tunnel axial forces results in oval distortion in tunnel segments, although a decrease in shear force and bending moment benefits the tunnel structure. Similarly, the interaction of parallel tunnels and the amplification influence on surface acceleration are particularly important during a seismic event. The interaction of parallel tunnels considerably impacts the distribution of internal force and the magnitude of neighbouring surface acceleration [10]. The influence of the underground structure on soil reactivity is significantly dependent on its depth, but has a significant impact on the surface in the range of around five times its width [11]. Also, the alignment of a new tunnel in a twin tunnel instance has a significant impact on the variance of stresses and settlements around the existing tunnel. Another study [12] determined the relative positions of twin tunnels using numerical analysis in three directions: horizontal alignment, vertical alignment, and inclined alignment. Settlement studies were conducted on the tunnels in these chosen orientations under various loading conditions. The construction of the upper tunnel led to a greater settling and bending moment. Vertically oriented tunnels had the most soil settling, whereas horizontally aligned tunnels had the least. Horizontal tunnel experiments revealed that as the distance between the two tunnels increased, surface soil settlement decreased. Beyond a certain distance, the building of the first tunnel had no bearing on the second tunnel. Similarly, the study by Hamdy [13] examined the effects of seismic waves on tunnel systems, particularly single and twin tunnels. Four cases were simulated, one for a single tunnel and three for twin tunnels. The horizontal, vertical, and diagonal alignments of twin tunnels were investigated to better understand the impact of seismic waves. The study found that following an earthquake, the tunnel lining experienced significant displacement, with shear force being the most impacted, followed by bending moment. Seismic activity has a less influence on the normal force of tunnel lining. It is clear that both static and seismic analysis of twin tunnels is critical, since the structural integrity of underground structures cannot be overlooked, particularly in seismically active areas.

2. METHODOLOGY

2.1 Numerical Modelling

In this research article, a2D plain strain soil tunnel model is created using GTS NX Midas (Finite Element Analysis software). The cross-section of the model is of 180X100m and has seven different layers with varying modulus of elasticity, modified from [14]. The variation of modulus of elasticity along with the depth of soil is taken into consideration as shown in Table1. Elasto-plastic Mohr-Coloumb soil condition is chosen from all the layers of soil. The various properties of soil considered for the study are listed in Table 2. The dimensions of tunnel are such that the diameter of the existing tunnel(D) is 6.26m [14] and the depth of the tunnel is 46.87m from the ground surface. 1D beam elements are selected for the tunnel to simulate linear behaviour of the tunnel lining. The dimensions of beam element used are 1X0.3m. The existing tunnel comprises of 40 such bending elements. No slip condition is considered between the tunnel lining and the surrounding soil. No groundwater table condition is considered for any layer of soil. Damping of 10% and 5% are assigned to each layer of soil and tunnel lining respectively. The important properties of the tunnel lining are thereby mentioned in Table 3. A new tunnel of same diameter is considered for the vertical twin tunnel system as shown in Figure 1. Here, the distance of the new tunnel, X_D is varied at 1.5D, 2D, 2.5D, 3D and 3.5D from the centre of the existing tunnel. (D = diameter of the existing tunnel and the new tunnel). In total, 6 different models are created.

After assigning the soil and tunnel properties, the model comprising of single tunnel and twin tunnel are finely meshed using 4-noded quadrilateral elements up to a maximum size of 1m. A high quality mesh is created to achieve the required accuracy, convergence, reduce the time and thereby expedite the process of simulation. The tunnels are meshed initially followed by the multiple soil layers. The mesh of tunnel lining is extracted from the soil excavation mesh.



(a)

(b)

Figure-1: Schematic layout of soil-tunnel model with (a) single tunnel (b) twin tunnel

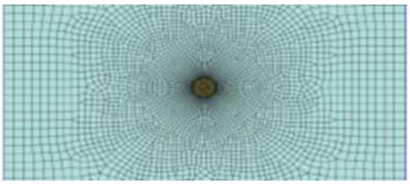


Figure-2: Mesh diagram

2.2 Seismic Input

Loma Preita earthquake (1989) is selected for the seismic anlysis. Since Delhi falls in seismic zone IV (IS 1893:2002, [15]), it is important to generate an artificial earthquake which is compatible for Delhi soils (alluvial silts) to generate realistic ground responses. Hence, with the help of SeismoMatch software response spectra compatible time history data is produced using Loma Preita earthquake data as shown in Fig.3. The original Loma Preita earthquake had a PGA of 0.367g whereas the artificial earthquake has a PGA of 0.125g. This artificially generated time history data has a total time period of 40sec. The earthquake is applied horizontally to the soil-tunnel model for a time duration of 12 seconds to fasten the computational process of the analysis as it is the predominant time period of the earthquake.

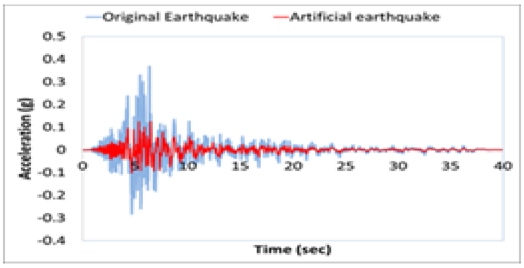


Figure-3: Loma Preita earthquake accelerogram

Table-1: Properties of each soil layer {modified from [14]}

Depth (m)	Thickness (m)	Elastic Modulus (kPa)
0-10	10	7500
10-20	10	15000
20-35	15	30000
35-50	15	40000
50-60	10	50000
60-80	20	65000
80-100	20	80000

Table-1: Mechanical properties of soil[14]

Properties	Values
Unit weight, γ_{bulk}	18kN/m^3
Saturated unit weight, γ_{sat}	20kN/m^3
Cohesion, c	0
Friction angle, Φ	35^o
Dilatancy angle, Ψ	5^o
Poisson's ratio, ν	0.25

Table-3: Properties of tunnel lining[14]

Properties	Values
Diameter of the single/existing tunnel, D	6.26m
Overburden depth, H	46.87m
Thickness of RC liners	0.28m
X_D (Centre to centre distance/ Diameter of the tunnel)	1.5 to 3.5
Elastic modulus of RC liners, E_C	3.16X10^7 kPa
Poisson's ratio of concrete	0.15

2.3 Analysis Procedure

For static analysis, all vertical boundary nodes are hinged in the x direction to allow for unhindered movement in the y-direction. The bottom border is fixed in all directions to simulate bottom rock condition. This is followed by Eigen value analysis, where ground surface springs are assigned to the soil model only. Now in case of seismic analysis, absorbent boundaries are placed at the vertical borders to replicate free field ground conditions. Various steps involved in the whole analysis are mentioned below:-

Step1: To create initial stresses, the at-rest earth pressure coefficient, "Ko condition" is considered by activating all soil layers. The soil excavation and lining are not active at this stage.

Step2: Soil from the first tunnel is removed. Volume contraction of 3% is used to represent the proportion of ground loss volume during excavation. The tunnel liner is assembled at the same time to prevent the tunnel cavity from collapsing.

Step3: Same step as mentioned in *Step 2* is repeated for the new tunnel located at a particular vertical distance.

Step4: Static analysis is carried out for the whole system and the resulting stresses get stored as the initial stress condition prior to the occurrence of earthquake.

Step5: Eigen value analysis is performed to generate dominant modes of frequencies, which are used to calculate mass and stiffness proportional coefficients, α and β respectively.

Step6: Non-linear time history analysis is performed by incorporating α and β from *Step5* and applying the artificially produced Loma Preita earthquake in the + x-direction to the soil-tunnel model.

3. RESULTS AND DISCUSSION

Static and seismic results produced in the existing tunnel lining after the construction of the new tunnel are presented in the form of lining forces such as axial force, bending moment, shear force and ground displacement contours of the surrounding soil medium.

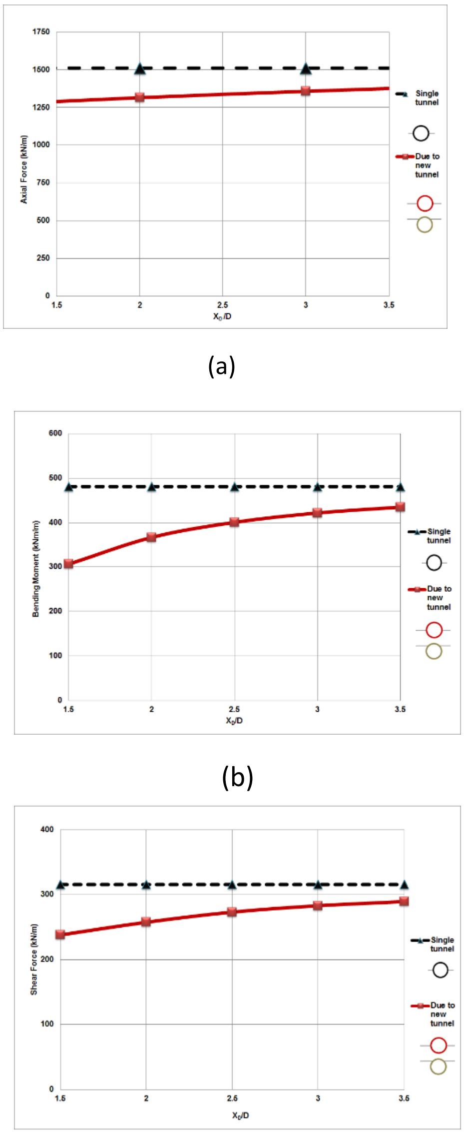
3.1 Static Analysis

The process of constructing a new tunnel requires the removal of the soil from its pathway. The removal of ground followed by the installation of tunnel lining alters the overall load distribution mechanism of the surrounding soil. This causes redistribution of stresses in the soil medium, which are then stored as initial stresses prior to the excavation of a new tunnel. So, the purpose of this research study is to determine the impact of constructing this new tunnel on the existing tunnel lining and the surrounding soil medium.

3.1.1 Tunnel Lining Forces

Static loads on tunnel linings, such as soil pressure and structural weight, are critical factors for assuring structural stability, safety, and long-term performance. Proper analysis through forces such as axil force, bending moment and shear force helps in efficient and reliable design of the tunnels.

Figure 4 (a) shows the variation of axial force with respect to XD in the existing tunnel lining, where XD is the ratio of centre-to-centre distance between the tunnels and the diameter of the tunnel (D). The variation of bending moment and shear force in the existing tunnel lining also show a similar pattern as shown in Figure 4 (b) and 4(c). It can be understood that due to construction of a new tunnel, the lining forces decrease in the existing tunnel in comparison to a single tunnel. This may be due to distribution of loads between the two tunnels, thereby generating lesser forces in the existing tunnel lining. Secondly, there is increase in lining forces increase with increase in XD. The gradual reduction of load sharing mechanism between the two tunnels as the soil bridge between them increases may lead to this pattern. It can be seen from the graphs that as the distance between the two tunnels increases, the lining forces of the existing tunnel in case of twin tunnel system slowly approach the values of the single tunnel.



(a)

(b)

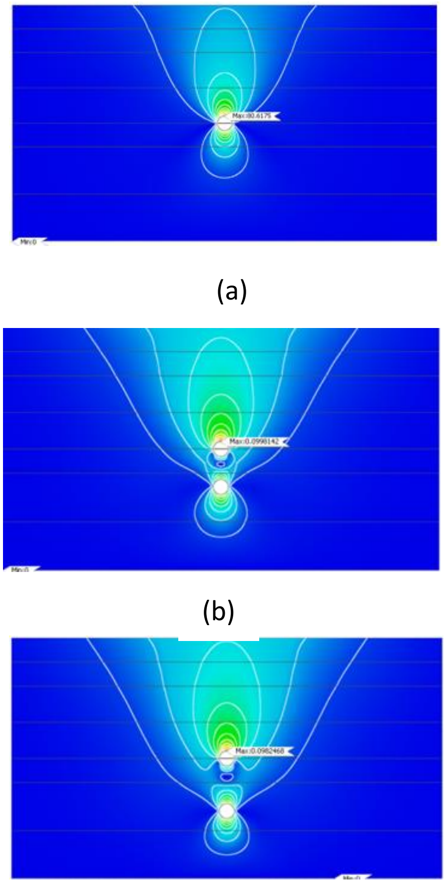
(c)

Figure-4: Variation of (a) Axial Force (b) Bending Moment (c) Shear Force in the existing tunnel lining due to construction of new tunnel

3.1.2 Ground Displacement Contours

Due to static loads, there occurs probable ground deformation which may result in different settlement patterns around the tunnels and the surrounding soil medium. Hence, it becomes imperative to analyse different displacement contours for proper analysis and efficient design.

Figure 5 shows the displacement contours in case of single tunnel and twin tunnel when a new tunnel is positioned at 1.5D, 2.5D and 3.5D from the existing tunnel. It can be seen that due to construction of a new tunnel, several displacement contours of same magnitude get shared between the two tunnels when the new tunnel is placed at 1.5D from the existing tunnel. But as the distance gradually increases from 2.5D to 3.5D, the contours get divided between the two tunnels. Also as shown in Figure 5 (a), the position of maximum total displacement is located at the crown of the single tunnel. However, in case of twin tunnel system, this position of maximum total displacement shifts to the crown of the new tunnel for each distance from the existing tunnel.



(a)

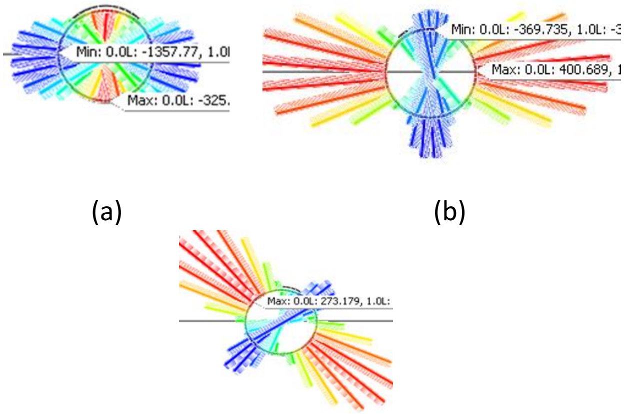
(b)

(c)

Figure-5: Variation of ground displacement contours in case of (a) single tunnel and a new tunnel of (b) 1.5D and (c) 3.5D

3.1. Locations of Maximum Forces

Figure 6 depicts the contours of axial force, bending moment and shear force in the existing tunnel when the new tunnel is placed at 2.5D.The position of maximum axial force with the highest magnitude is located at the left springline of the existing tunnel and is of compressive nature. Similarly, the position of maximum bending moment is located at the right springline of the existing tunnel and is hogging in nature. The position of maximum shear force is located at +45º to the left springline of the existing tunnel and is positive in nature.



(a) (b)

(c)

Figure-6: Contours of (a) Axial Force (b) Bending Moment (c) Shear Force in the existing tunnel

3.2 Seismic Analysis

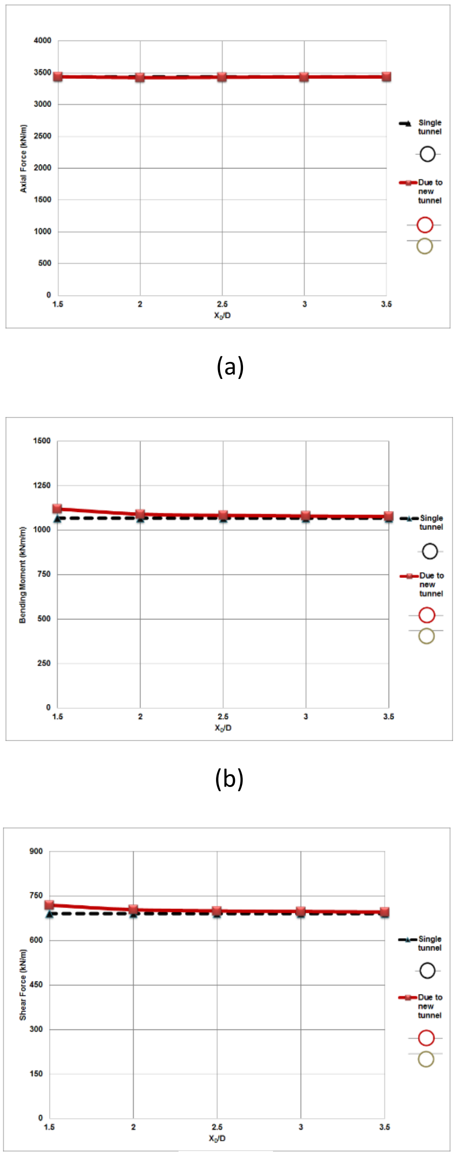
The single and the twin tunnel models are then seismically analyzed by non-linear time history analysis with the help of Loma Preita earthquake. The tunnel lining forces of the existing tunnel and ground displacement contours are compared.

3.2.1 Tunnel Lining Forces

The variation of lining forces in the single tunnel and twin tunnel under earthquake are compared in Figure 7. As seen in Figure 7 (a), the variation of axial force in the single tunnel and existing tunnel in case of twin tunnel is almost same. Axial force generally depends on the overburden stress from the soil on the tunnel lining which does not undergo any significant change due to the horizontally applied earthquake. Hence, there is negligible difference in the variation of axial force between the single tunnel and twin tunnel under the seismic load.

However, in case of bending moment and shear force, there is a slight increase in existing tunnel of the twin tunnel system as compared to the single tunnel. The difference in the values of the forces is very low and is significant only when the distance between the two tunnels is 1.5D to 2D.

It can be observed that when the two tunnels are extremely close to each other, the existing tunnel in case of twin tunnel experiences greater seismic load as compared to a single tunnel. This may be attributed to the fact that there is an increase in the interference of stresses between the two tunnels under the horizontal earthquake load. Also, as the distance between the two tunnels exceeds 2D, it is noticed that the vertical positioning of the new tunnel below the existing tunnel is of not much significance to the existing tunnel under earthquake. Hence, it can be concluded that in case of earthquake, the performance of the existing tunnel is independent of the new tunnel when placed below it at different spacing.



(a)

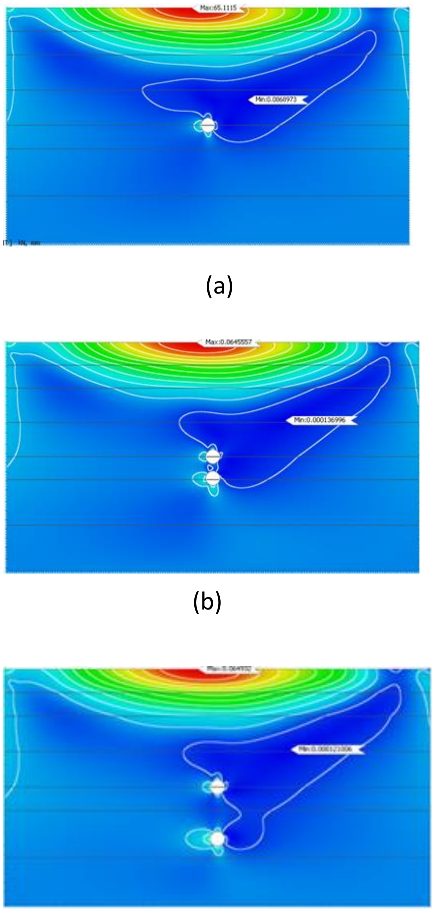
(b)

(c)

Figure-8: Variation of (a) Axial Force (b) Bending Moment (c) Shear Force in the existing tunnel lining after earthquake

3.2.2 Ground Displacement Contours

Figure 9 shows the various displacement contours of the single tunnel and the twin tunnel when the new tunnel is placed at 1.5D, 2.5D and 3.5D from the existing tunnel. It is observed from Figure 9 (a) to 9(b) that under the influence of earthquake, the soil medium around the twin tunnel experiences a lot of disturbance as compared to a single tunnel. Also, as the distance between the two tunnels increases, the soil around the new tunnel undergoes greater displacement contours due to the experience of greater vertical load.



(a)

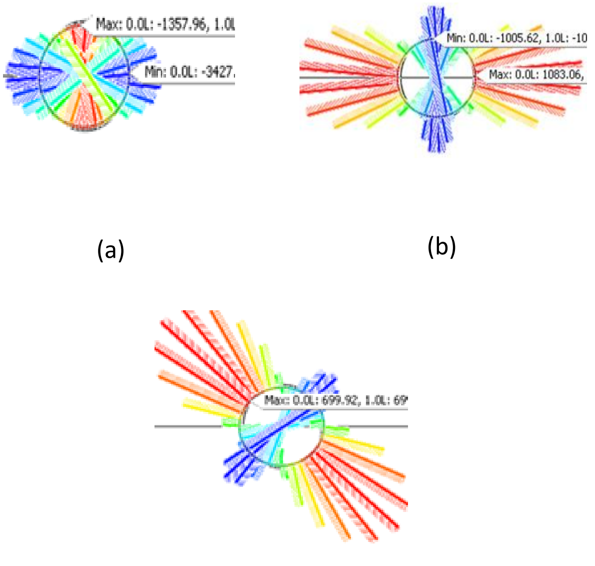
(b)

(c)

Figure-9: Variation of ground displacement contours in (a) single tunnel and new tunnel is at (b) 1.5D and (c) 3.5D

3.2.3 Locations of Maximum Forces

Figure 10 represents the contours of axial force, bending moment and shear force in the existing tunnel when a new tunnel is placed at 2.5D from it. The position of greatest magnitude of axial force shifts to the right springline of the existing tunnel and is compressive in nature as compared to the static case. But in case of bending moment and shear force, the position remains same. Figure 10 (b) shows that the position of maximum bending moment is located at the right springline of the existing tunnel. Similarly, Figure 10 (c) shows that the postion of maximum positive shear force is located at +45º of the left springline of the existing tunnel lining.This may be due to the horizontal direction of the earthquake as the earthquake impacts the existing tunnel from the +x-direction and hence, the effect is more at those locations.



(a) (b)

(c)

Figure-10: Contours of (a) Axial Force (b) Bending Moment (c) Shear Force in the existing tunnel lining after earthquake

From the results of static analysis, it can be understood that after the distance of 2.5D, the difference in variation of all the parameters between the existing tunnel and twin tunnel gradually decrease. However, in case of seismic analysis, the variation between single tunnel and the existing tunnel in twin tunnel decreases after 2D. It is essential to find a safe distance between the existing tunnel and the new tunnel to ensure static and seismic stability. Hence, according to the current research article, an optimum distance of 2.5D-3D between the existing tunnel and a new tunnel will be ideal to be both statically and seismically safe. The result is largely dependent on the output of static analysis.

4. SUMMARY AND CONCLUSIONS

Tunnels are very essential underground structures which require comprehensive research, especially in an earthquake-prone zone to avoid any kind of risk to possible damage due to any seismic load. Therefore, in this article, static and seismic comparisons of a single and a twin tunnel system are carried out. The impact is observed on the existing tunnel due to a new tunnel of same diameter when placed at different vertical distances below the existing tunnel. Artificially produced response spectra compatible Loma Preita earthquake data is used in the non-linear time history analysis. The interaction effect is studied in the form of parameters such as lining forces and ground displacement contours. Based on the above research, it can be concluded that:

In case of static analysis:

- After construction of a new tunnel, lining forces of the existing tunnel such as axial force, bending moment and shear force decrease as compared to a single tunnel. This is due to distribution of vertical loads after construction of the new tunnel.
- Lining forces of the existing tunnel tend to increase on increasing the distance between the tunnels. This results from gradual reduction in load sharing mechanism from the increasing soil bridge between the tunnels.
- Displacement contours are initially shared between the two tunnels but as the distance between them increases, they get distributed between the two tunnels.

In case of seismic analysis:

- Axial force in a single tunnel is similar to that in the existing tunnel of a twin tunnel system. This may be due to lack of much significant difference in overburden stress on the existing tunnel lining from the horizontally applied earthquake.
- But, the bending moment and shear force of twin tunnel system are higher than the single tunnel when the distance between the two tunnels varies from 1.5D to 2D. Beyond 2D, these forces in the existing tunnel of the twin tunnel behave similar to that in the single tunnel. Hence, after a distance of 2D, the behaviour of existing tunnel is independent of the vertical positioning of the new tunnel below it under a horizontal earthquake load.
- Under the seismic load, the soil around the twin tunnel experiences greater disturbances as compared to a single tunnel. Also, as the distance between the two tunnel increases, the soil around the new tunnel undergoes greater displacements as compared to the existing tunnel.

Based on this research study, it can be concluded that an optimum distance of 2.5D-3D will be ideal for construction of a new tunnel of same diameter vertically below an existing tunnel to counter both static and seismic loads safely.

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