STATIC AND SEISMIC EVALUATION OF AN EXISTING TUNNEL DUE TO A NEW TUNNEL OF DIFFERENT DIAMETERS

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Abstract

The construction of tunnels has gained importance due to their wide variety of uses in the current world of transportation and communication. However, the seismic vulnerability of these underground tunnels is of paramount importance, as they are susceptible to various damages. Hence, in this present article, static and seismic analysis of an existing tunnel is carried out in the absence and presence of a new tunnel of different diameters and placed at different horizontal locations from the existing tunnel. A 2D plain strain model is created using GTS NX Midas. The soil properties resemble Delhi silt and the earthquake used is the Loma Preita earthquake. Response-spectra compatible earthquake data is generated using SeismoMatch software. The response parameters are generated in the form of tunnel lining forces such as axial force, bending moment, shear force and ground displacement contours. In case of static analysis, it is observed that due to a new tunnel, the lining forces in the existing tunnel increase, whereas a new bigger tunnel creates greater lining forces in the existing tunnel than a new smaller tunnel. In contrast to static analysis, during seismic analysis it is observed that the bending moment and shear force show a reverse pattern. Therefore, it can be understood that the size and spacing of the new tunnel plays a very significant role in the static and seismic stability of the existing tunnel.

Keywords: twin tunnel, alluvial silts, static and seismic analysis.

1 INTRODUCTION

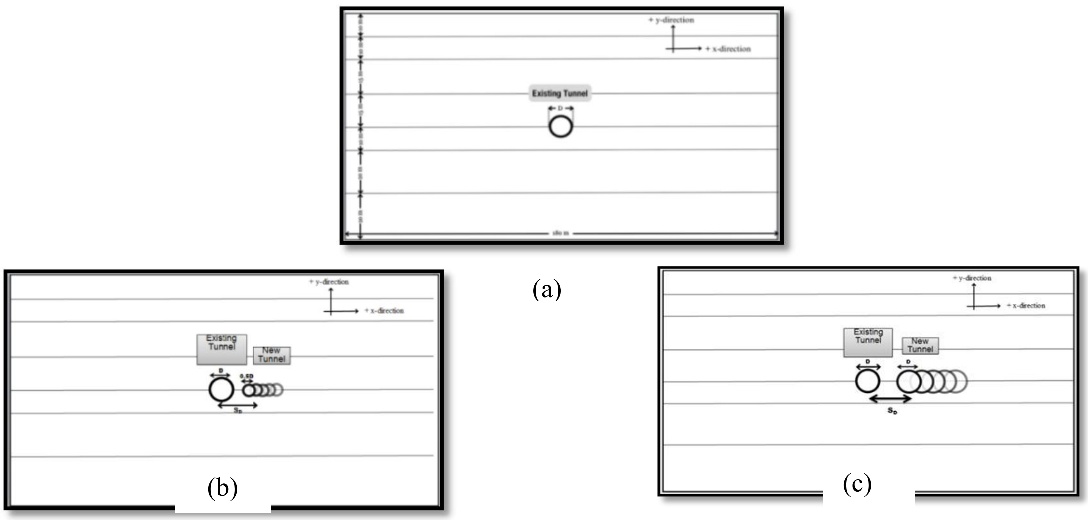
The advent of underground tunnels dates back to 2200B.C. Since then they have found their usage for various modes of transportation and communication. Due to increase in urbanisation, there is an increase in shortage of aboveground space for further development of modes of communication and other utility services. Hence, in the light of modern era, there is an increasing demand of underground structures, especially tunnels to meet the different needs of development. Throughout many years, it was assumed that underground structures are seismically safer than aboveground structures due to the natural constraint provided by the surrounding soil or rock. But, there have been wide number of incidents where significant damages have occurred to the tunnel due to earthquakes. Hashash (Hashash et al., 2001) has listed several such examples of tunnel damages in the recent years due to earthquakes.

Seismic waves can cause impacts on the structure due to the existence of a new adjacent opening that exceed those estimated for a single tunnel. There has been a research which focuses on predicting induced stresses in existing tunnel structures under seismic events while considering the excavation of a new neighbouring tunnel (Zlatanović et al., 2021). However, Corigliano in (Corigliano et al., 2011) found that simpler methodologies can produce satisfactory results for the seismic analysis of deep tunnels, but a thorough computation of the dynamic increase of internal stresses on the lining is required for stable design in seismically active areas. The study examines several techniques of analysis, such as basic approaches and complex numerical simulations, to determine the seismic stress increment and the dependability of pseudo-static solutions. Also, Bobet conducted a study (Bobet, 2003) which introduces novel mathematical approaches for assessing the impact of pore water pressure on tunnel stability under static and seismic loads. The paper examines the drainage conditions at the ground-liner interface, as well as the effect of groundwater pressure on the ground and support responses. Similarly, the study conducted in (Jishnu & Ayothiraman, 2018) focuses on seismic analysis of deep twin tunnels in Indian cities such as Delhi, taking into account specific soil characteristics and employing a pseudo-static method. The study quantifies the extra moments, thrusts, shear, and surface displacements induced by earthquake loads on the tunnel liner, emphasizing the need of including seismic loading into twin tunnel designs. Wang in (Wang, 1993) estimated the maximum bending moments were estimated using the full-slip closed form solution and compared to those obtained by no-slip finite difference analysis. The full-slip assumption produced larger bending moments than the no-slip assumption. The full-slip assumption caused somewhat greater ovaling (distortion) of the lining, although the changes were negligible. The research in (Singh et al., 2021) investigates the impact of constructing a second tunnel, either horizontally or vertically aligned, following the construction of the existing first tunnel on the reaction of the existing tunnel. The study is performed in both static and seismic circumstances by varying the pillar width between the tunnels. The research demonstrates that after an earthquake, vertical stresses at key locations and forces in tunnel lining of horizontally aligned twin tunnels increase for a pillar width equal to half the tunnels' diameter. The vertical stresses and forces in the lining of the first tunnel also increase with increase in the pillar width. Bazaz and Besharat conducted a research in (Bazaz & Besharat, 2008) which studies the seismic analysis of shallow tunnels in a soil medium, with a particular emphasis on the behaviour of circular cross-section tunnels during operation by comparing the results of a numerical analysis with the analytical solutions provided by Penizen and Wang. The results reveal a relative error in the analytical methods, and increasing soil stiffness lowers the produced circular stress in the lining. This is also proved in (Azadi & Kalhor, 2014) which states that axial force in the tunnel lining decreases considerably when soil cementation increases. Also, a decrease in tunnel axial forces causes oval distortion in tunnel segments, although a decrease in shear force and bending moment improves the condition of the tunnel structure. Similarly, the interaction of parallel tunnels and the amplification impact on surface acceleration plays a very significant role during a seismic event. The interaction of parallel tunnels significantly affects the distribution of internal force as well as the amplitude of adjacent surface acceleration (Li et al., 2022). The impact of the underground structure on soil reaction greatly depends on its depth but has a substantial impact on the surface in the range of about five times its width (Sun et al., 2020). Also, the alignment of a new tunnel in a twin tunnel case plays an important role in the variation of stresses and settlements around the existing tunnel. The research carried out in (Pm Channabasavaraj & Visvanath, 2013) evaluated through numerical analysis the relative positions of twin tunnels in three directions: horizontal alignment, vertical alignment, and inclined alignment. Settlement study was performed for various loading circumstances on the tunnels in these chosen orientations. It emerged that the construction of the top tunnel resulted in increased settlement and bending moment. Vertically oriented tunnels had highest soil settlement, while horizontally aligned tunnels had the lowest. In horizontal tunnel investigations, it was shown that as the distance between the two tunnels increased, surface soil settlement decreased. Beyond a certain distance, the construction of the first tunnel had no impact on the second tunnel. Similarly, the study carried out by Hamdy (Hamdy et al., 2015) investigated the effects of seismic waves on tunnel systems, especially single and twin tunnels. Four examples were simulated: one for a single tunnel and three for twin tunnels. The horizontal, vertical, and diagonal alignments of twin tunnels were studied to better understand the influence of seismic waves. The study indicated that after an earthquake, the tunnel lining experienced increased displacement, with shear force being the most affected, followed by bending moment. Seismic activity has a lower impact on the normal force of tunnel lining. It can be understood that both static and seismic analysis of twin tunnels is of pivotal importance as the structural stability of the underground structures cannot be underestimated especially in a seismically active area.

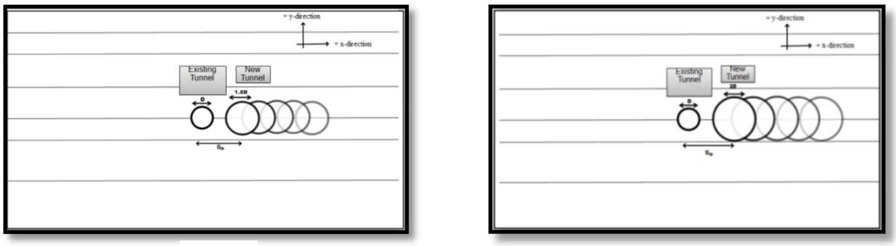
2 METHODOLOGY

2.1 NUMERICAL MODELING

In this research article, a 2D plain strain soil tunnel model is constructed using GTS NX Midas (Finite Element Analysis software). The layout of the model comprises of a cross-section of 180X100m. The model consists of seven different layers with varying modulus of elasticity, modified from [14].



(a) (b) (c)



(d) (e)

Figure.1 Schematic diagram of soil-tunnel model in case of (a) Single tunnel and twin tunnel system where the diameter of new tunnel is (b) 0.5D (c) 1D (d) 1.5D (e) 2D placed at varying S_D

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 model are listed in Table 2. The dimensions of tunnel are selected from (Singh et al., 2017) where the diameter of the existing tunnel(D) is 6.26m 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. Perfect bond is considered between the tunnel lining and the surrounding soil. Ground water table is not considered. 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 varying diameters, ranging from 0.5D-2D is considered in the horizontal twin tunnel arrangement as illustrated in Figure.1. Here, the distance of the new tunnel, S_D is varied at $1.5D_{avg}$, $2D_{avg}$, $2.5D_{avg}$, $3D_{avg}$ and $3.5D_{avg}$ for each diameter from the centre of the existing tunnel. (D_{avg}= Average diameter of the existing tunnel and the new tunnel). In total, 21 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.

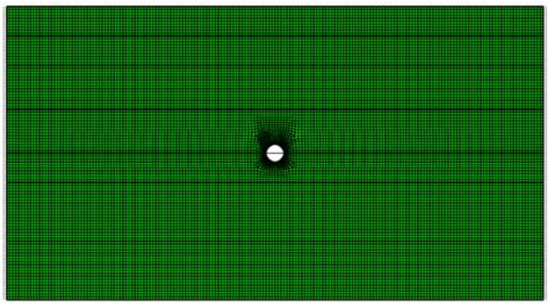


Figure. 2 Mesh diagram of soil and tunnel before excavation

2.1 SEISMIC INPUT

Loma Preita earthquake (1989) is chosen for the non-linear time history analysis. Since Delhi falls in seismic zone IV (IS 1893:2002, (IS-1893-Part-1, 2002)), it is important to generate an artificial earthquake which is compatible for Delhi soils (alluvial silts) to result in realistic ground responses. Hence, with the help of SeismoMatch software response spectra compatible time

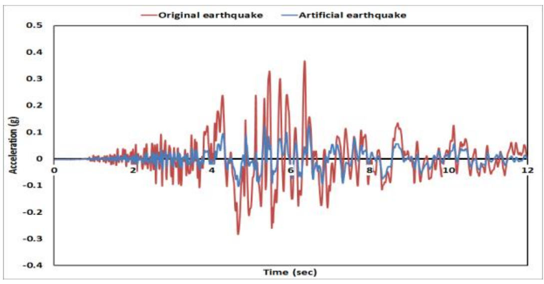


Figure. 3 Accelerogram of Loma Preita Earthquake

history data is produced using Loma Preita earthquake data as shown in Figure.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 12 seconds to speed up the computational process of the investigation because that was the predominant time period of the earthquake.

Table1 Properties of each soil layer {modified from (Singh et al., 2017)}

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

Table2 Mechanical properties of soil(Singh et al., 2017)

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

Table3 Properties of tunnel lining(Singh et al., 2017)

Properties	Values
Diameter of the single/existing tunnel, D	6.26m
Diameter of the new tunnel	0.5D to 2D
Overburden depth, H	46.87m
Thickness of RC liners	0.28m
S_D (Centre to centre distance/Average Diameter of both the tunnels)	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 replicate bottom rock condition. This is followed by Eigen value analysis, where ground surface springs are applied to the soil model only. Now in case of seismic analysis, absorbent boundaries are placed at the vertical borders to imitate free field ground conditions. Various phases involved in the whole analysis are mentioned below:-

Phase1: To create initial stresses, the at-rest earth pressure coefficient, "Ko condition" are considered by activating all soil layers. The soil excavation and lining are not active at this stage.

Phase2: 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.

Phase3: Similar steps as mentioned in *Phase 2* are repeated for every new tunnel of each specific diameter at a particular distance.

Phase4: 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.

Phase5: Modal analysis is performed to generate dominant modes of frequencies, which are used to calculate mass and stiffness proportional coefficients, α and β respectively.

Phase6: Non-linear time history analysis is finally performed by incorporating α and β from *Phase5* and applying the artificially generated earthquake in the positive x-direction to the soil-tunnel model.

Phase7: *Phase1* to *Phase6* is repeated for every new tunnel of a different diameter placed at different horizontal locations.

3 RESULTS AND DISCUSSION

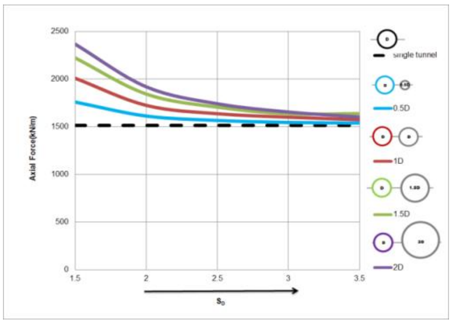
Static and seismic responses generated in the existing tunnel lining due to the construction of the new tunnel are presented in the form of lining forces such as axial force, bending moment, shear force and ground displacement contours of the soil medium.

3.1. Static Analysis

The process of building a new tunnel necessitates the removal of the ground from its pathway. The removal of soil 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.

Figure.4 (a) shows the variation of axial force with respect to S_D in the existing tunnel lining, where S_D is the ratio of centre-to-centre distance between the tunnels and the average diameter of both the tunnel (D_{avg}). 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 is noted that firstly, due to excavation and construction of a new tunnel, the axial force, bending moment and shear force increase in the existing tunnel. This may be due increase in interference of stresses due to construction of a new tunnel, thereby generating greater forces in the existing tunnel lining. Secondly, the increase in the lining forces decreases with increase in S_D. The gradual reduction of interference of stresses between the two tunnels as the soil bridge between them increases may lead to this pattern.

Thirdly, it is observed that a new tunnel of bigger diameter produces greater lining forces in the existing tunnel lining than a new tunnel of smaller diameter. As seen in Figure.4 (a), a new tunnel of 2D diameter generates greater axial force in the existing tunnel in comparison to a new tunnel of 0.5D, 1D or 1.5D. Same pattern is also observed for bending moment and shear force as shown in Figure.4 (b) and (c). This can be understood from the fact a bigger tunnel results in greater unloading and reloading of soil during construction. Hence, the construction of a new bigger tunnel creates greater lining forces on an existing tunnel under static loads.



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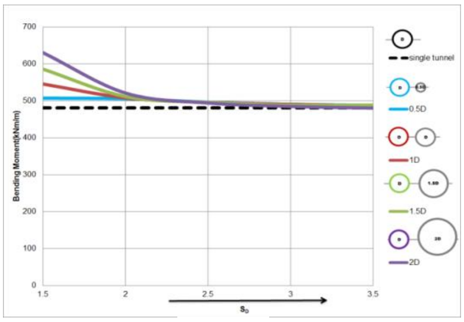

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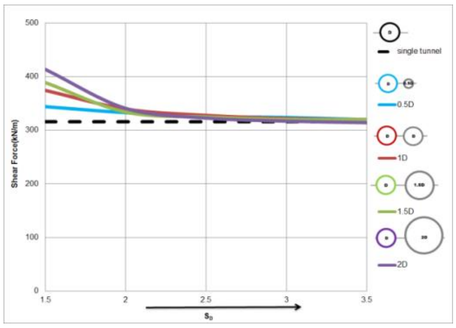
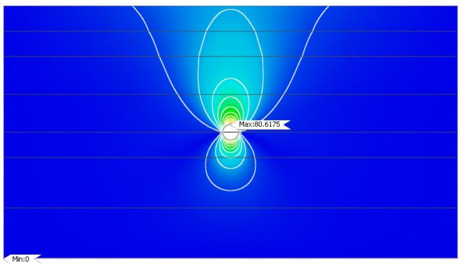


(c)

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

Figure.5 shows the displacement contours in case of single tunnel and twin tunnel when a new tunnel of each diameter is placed at $2.5D_{avg}$ from the existing tunnel. It is observed that due to construction of a new tunnel, several displacement contours of same magnitude get shared between the two tunnels and as the diameter of the new tunnel increases, greater displacement contours are observed around the bigger tunnel. Also, in case of single tunnel as seen in Figure.5 (a), the maximum total displacement is observed at the periphery of the existing tunnel. However, this position of maximum total displacement shifts to the crown of the new tunnel as the diameter of the new tunnel as the diameter of the new tunnel becomes equivalent to that of the existing tunnel and exceeds to 1.5D and 2D. Similar responses are observed for all other cases.



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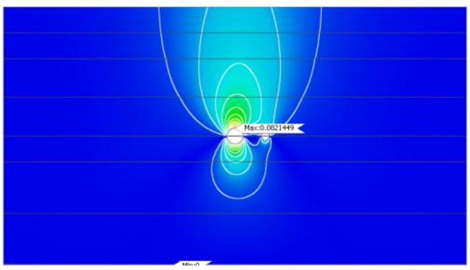

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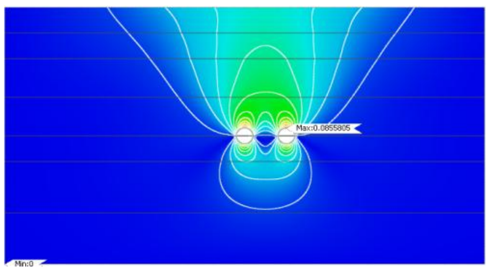

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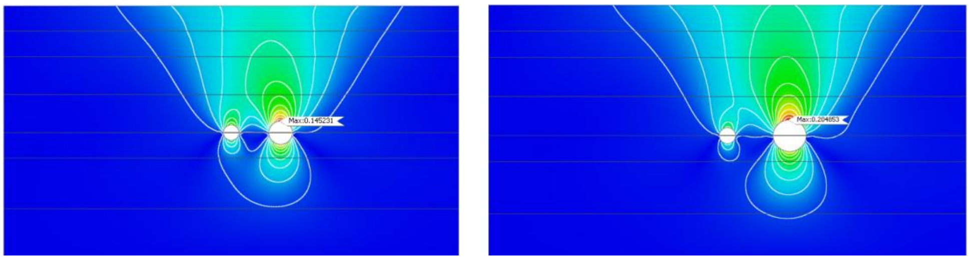
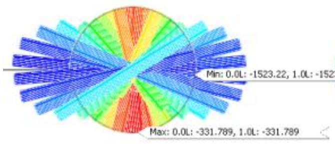


(d) (e)

Figure.5 Variation of displacement contours in the soil medium of (a) Single tunnel and twin tunnel system where the diameter of new tunnel is (b) 0.5D (c) 1D (d) 1.5D and (e) 2D placed at $2.5D_{avg}$

Fig.6 shows the contours of axial force, bending moment and shear force in the existing tunnel and the new tunnel of same diameter placed at $2.5D_{avg}$.. The position of maximum axial force with the greatest magnitude is observed at the springline of the existing tunnel and is of compressive nature. Similarly, the position of maximum bending moment is located at the springline of the existing tunnel and is hogging in nature. The position of maximum shear force is located at -45º to the springline of the existing tunnel and is positive in nature.



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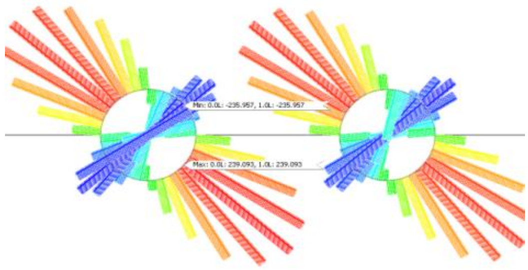
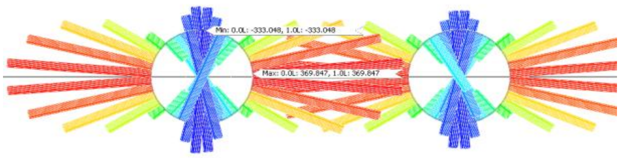
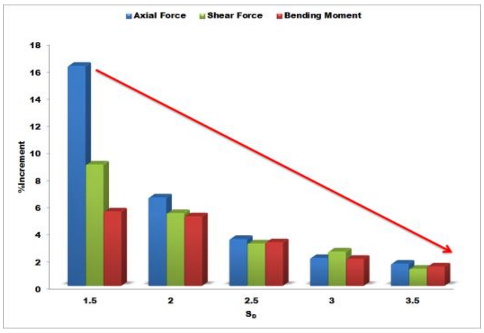




(c)

Figure.6 Contours of (a) Axial Force (b) Bending Moment (c) Shear Force in case of twin tunnels.

Fig.7 (a) to 7(d) represents the percentage increment of lining forces in the existing tunnel due to the new tunnel varying from 0.5D to 2D. It can be understood that in all the cases, the difference in the lining forces between the existing tunnel of twin tunnel system and the single tunnel is gradually decreasing as the distance between the two tunnels is increasing. This is represented by the red arrow in all the cases. It can thus be stated that in case of static loads, as the distance between the two tunnels increases, the existing tunnel slowly behaves like that of a single tunnel. Also, the axial force in the twin tunnel system seems to have the maximum variation when the new tunnel is placed at $1.5D_{avg}$ from the existing tunnel.



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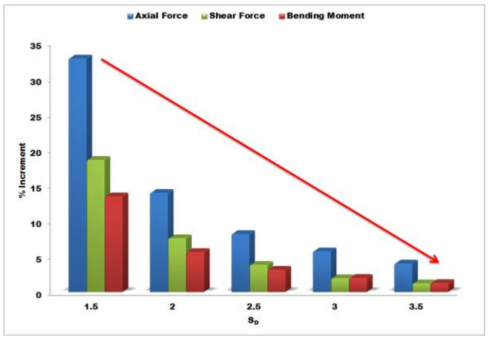

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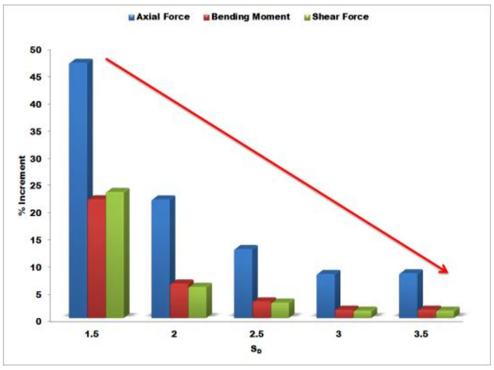

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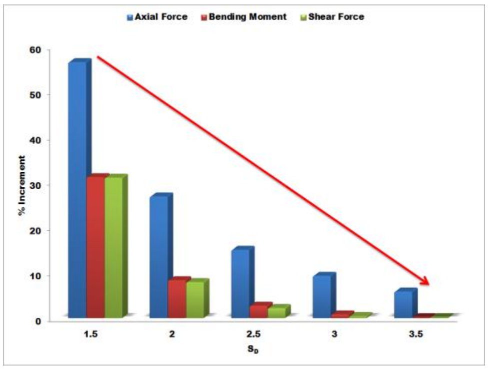


(d)

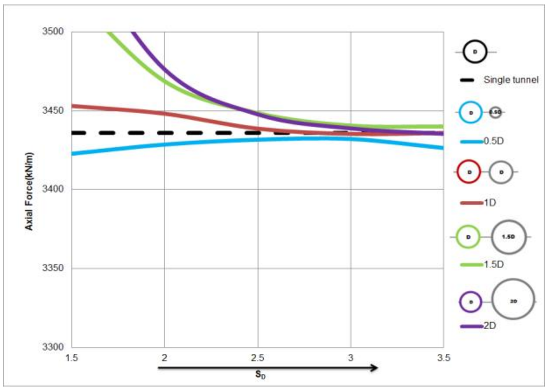
Figure.7 Variation of % increment of lining forces in case of existing tunnel in twin tunnel system with a new tunnel of diameter (a) 0.5D (b) 1D (c) 1.5D (d) 2D when compared with a single tunnel.

3.2. Seismic Analysis

The single and the twin tunnel models are further seismically analyzed by non-linear time history analysis using Loma Preita earthquake. The tunnel lining forces of the existing tunnel and ground displacement contours are compared. The variation of axial force in the single tunnel and twin tunnel is shown in Figure.8 (a). In case of twin tunnel, it is seen that when a new tunnel is placed near an existing tunnel, the axial force increases in the existing tunnel lining except for when the new tunnel is smaller than the existing tunnel. Also, as the distance between the two tunnels increases, the axial force gradually decreases. The variation of axial force in case of earthquake does not show much variation from that of static analysis, as the axial force of the tunnel lining depends generally on the overburden stress from the soil. This overburden stress does not suffer much change due to the horizontally applied earthquake.

Contrary to the variation of axial force, the bending moment and shear force in the existing tunnel show a reverse pattern. In case of earthquake, due to construction of a new tunnel, the bending moment and shear force in an existing tunnel lining decrease than that in a single tunnel. In case of single tunnel system, the existing tunnel solely carries the seismic load in contrast to a twin tunnel system where the load gets shared between the tunnels. This helps in generating lower bending moment in the twin tunnel system.

Moreover, as the distance between the two tunnels increases, these two lining forces increase. As the distance between the two tunnel increases, the existing tunnel in case of twin tunnel becomes more vulnerable to the horizontal earthquake force and therefore, the tunnel lining produces higher bending moment. Also, it is observed that lower bending moment is generated in the existing tunnel due to construction of a new bigger tunnel than a new smaller tunnel in case of earthquake. The construction of a new bigger tunnel in a twin tunnel system results in greater absorption of seismic energy as compared to a new smaller tunnel. Hence, it can be concluded that a horizontal twin tunnel is seismically safer than a single tunnel in case of a horizontally applied earthquake.



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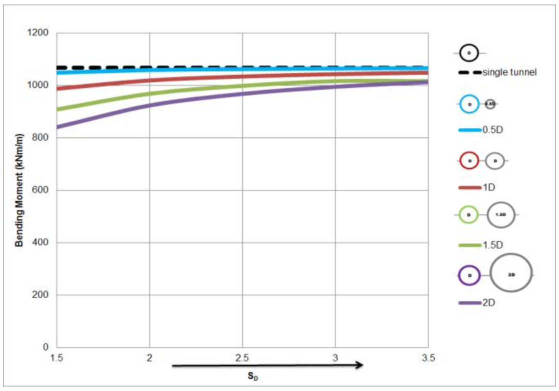


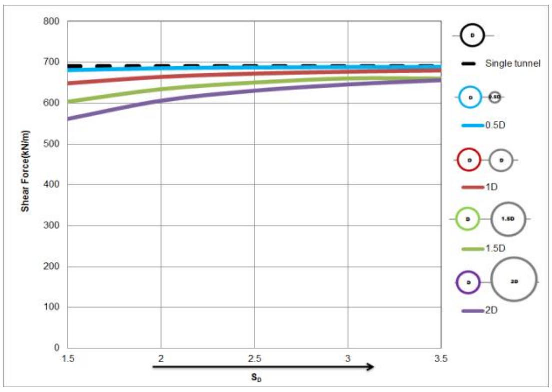
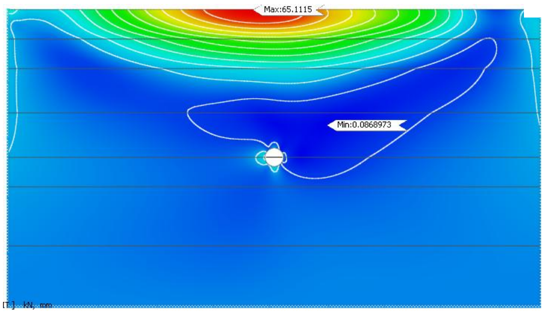


Figure.8 Variation in (a) Axial Force (b) Bending Moment (c) Shear Force in the existing tunnel due to a new tunnel after earthquake.

Figure.9 shows the various displacement contours of the single tunnel and the twin tunnel with the new tunnel of each diameter placed at $2.5D_{avg}$ from the existing tunnel. It can be understood from Figure.9 (a) to 9(c), that the soil arund the existing tunnel and the new tunnel does not undergo much variation in disturbance due to the earthquake. Whereas in Figure.9 (d) and (e), it can be seen that the soil around both the tunnels suffer extensive disturbance when a new bigger tunnel is constructed near the existing tunnel. This can be attributed to greater reflection of seismic waves by the new bigger tunnrls.

(b) (c)



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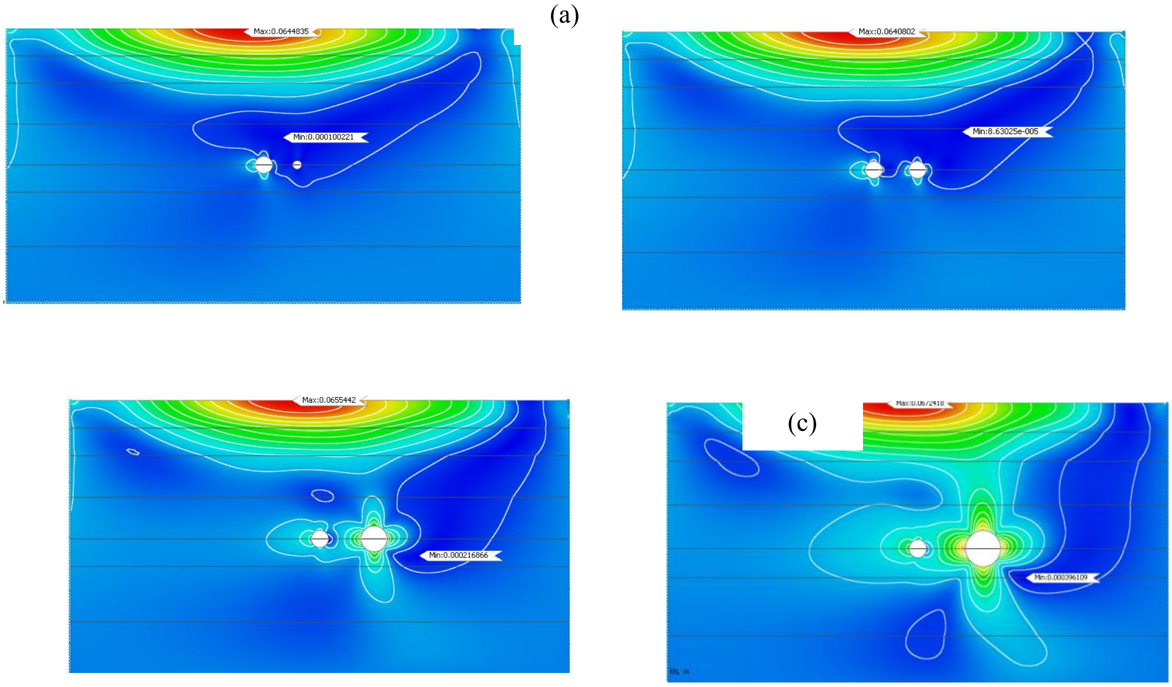
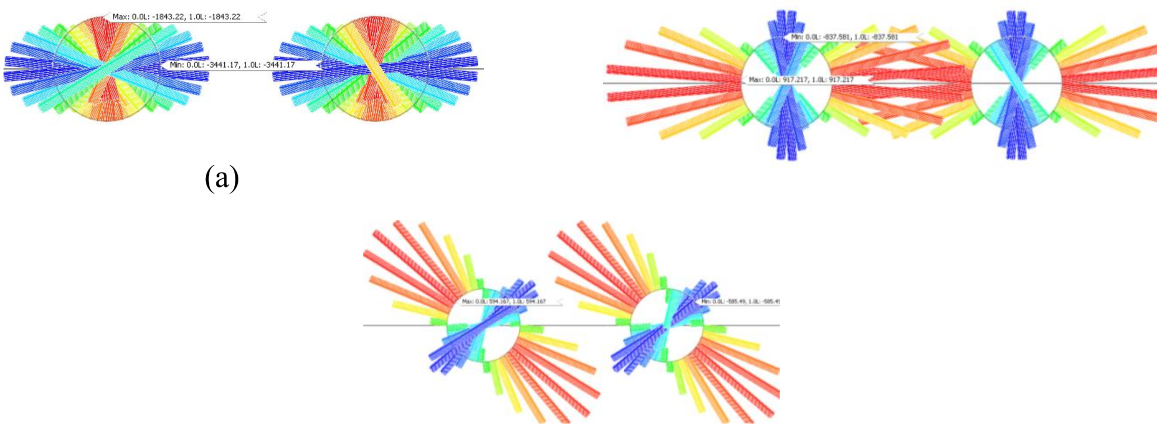


(d) (e)

Figure.9 Variation in ground displacement contours in case of (a) single tunnel and twin tunnel with a new tunnel of diameter (b) 0.5D (c) 1D (d) 1.5D (e) 2D when placed at 2.5D_{avg} after the earthquake

Figure.10 depicts the contours of axial force,bending moment and shear force when a new tunnel of same is placed at 2.5D_{avg}. The position of highest magnitude of axial force remains at the springline of the existing tunnel and is compressive in nature, similar to the static case. But contrast to the static case, the position of maximum bendingmoment and shear force shifts to the opposite direction. Figure.10 (b) shows that the position of maximum bending moment is located at the left 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 can be attributed 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.However, axial force largely depends on the overburden stress from the soil and hence, does not show any alteration in its position of maximum impact.

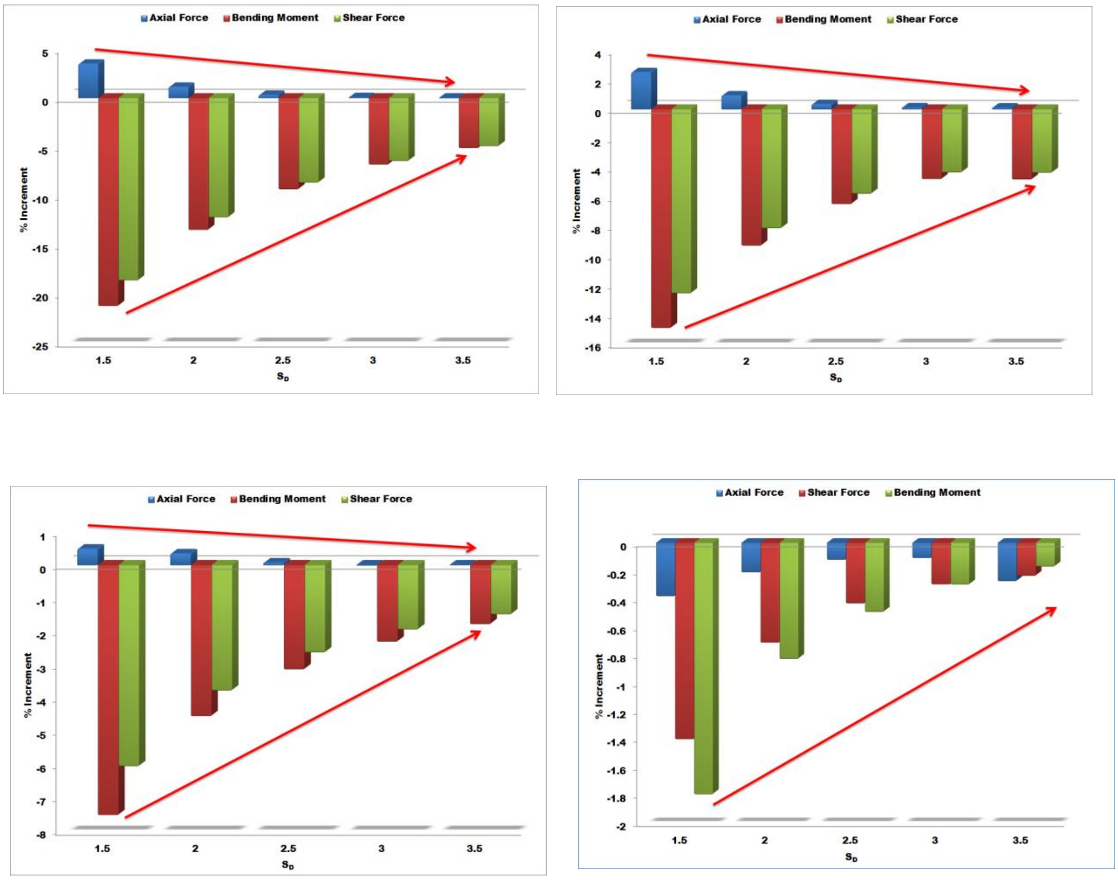


(a)

(c)

Figure.10 Contours of (a) Axial Force (b) Bending Moment and (c) Shear Force in the twin tunnels after earthquake

Figure.11 represents the variation of percentage increment of lining forces when the new tunnel of each diameter is placed at different spacings. Its can be understood from Figure.11 (a) that when the new tunnel is of 0.5D, the % increment in axial force, bending moment and shear force in the existing tunnel is negative and it decreases as the distance between the two tunnels increases. This implies that the lining forces of single tunnel is greater than the existing tunnel of the twin tunnel system as shown in Figure.8.



(c) (d)

Figure.11 Variation in %increment of lining forces in the existing tunnel when the diameter of new tunnel is (a) 0.5D (b) 1D (c) 1.5D (d) 2D as compared to a single tunnel after earthquake

The red arrow in the graph symbolizes the decreasing pattern of the lining forces against the increasing distance between the tunnels. But as the diameter of the new tunnel changes to 1D, 1.5D and 2D, the percentage increment in axial force turns positive in contrast to bending moment and shear force, which remain negative. This means that the axial force in the existing tunnel lining of the twin tunnel system is greater than that in the single tunnel as seen in Figure.8 (a). However, the percentage variation of bending moment and shear force is negative which means that the single tunnel has greater bending moment and shear force than the existing tunnel in twin tunnel system as seen in Figure.8 (b) and 8(c). The difference in variation decreases as the distance between the tunnels increases , which highlights the fact that as the distance between the two tunnels increases, the existing tunnel in the twin tunnel system behaves like the single tunnel.

From the results of static analysis, it is 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. Same is observed in case of seismic analysis. 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 present research study, 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.

4 SUMMARY AND CONCLUSIONS

Tunnels are important underground structures which require extensive research study, especially in an earthquake-prone zone to avoid any possible damage due to any seismic load. Hence, in this article, static and seismic results of a single and a twin tunnel system are compared. The impact is observed on the existing tunnel due to a new tunnel of different diameters placed at various horizontal distances. Artificially generated 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 study, 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 increase as compared to a single tunnel. This is due to increment in interaction of stresses after construction of the new tunnel.

- Lining forces of the existing tunnel tend to decrease on increasing the distance between the tunnels. This results from gradual decrease of interference of stresses from the increasing soil bridge between the tunnels.

- Greater lining forces in the existing tunnel occur due to construction of a new bigger tunnel nearby as compared to those created by a new smaller tunnel. A new bigger tunnel creates greater disturbance in the soil around the existing tunnel as compared to a new smaller tunnel and hence, existing tunnel lining creates greater resisting forces to those disturbances.

In case of seismic analysis:

- Axial force in a single tunnel is lower than that in the existing tunnel of a twin tunnel system except for a new tunnel of diameter 0.5D. 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 lower than the single tunnel. These forces tend to increase on increasing the distance between the two tunnels. In case of twin tunnel system, the new tunnel acts as a reinforcing force to the existing tunnel against the horizontal earthquake. Hence, twin tunnel system generates lower bending moment than the single tunnel. Also, as the distance between the tunnel increases, the existing tunnel in the twin tunnel case gradually behaves like a single tunnel and therefor, these lining forces slowly approach the values of single tunnel.

- A new bigger tunnel placed horizontally near an existing tunnel produces lower bending moment in the existing tunnel lining as compared to a new smaller tunnel. This can be attributed to the fact that a new bigger tunnel absorbs greater seismic energy than a new smaller tunnel, and therefore, the existing tunnel reacts to a lower seismic force consequently in the form of lower bending moment and shear force.

Based on this research article, it can be concluded that an optimum distance of 2.5D-3D will be ideal for construction of a new tunnel of any diameter, ranging from 0.5D to 2D, horizontally next to an existing tunnel to counter both static and seismic loads safely.\

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Compliance with Ethical Standards

Conflict of interest
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