

**FINITE ELEMENT ANALYSIS OF UNDERGROUND TWIN TUNNEL
SUBJECTED TO SEISMIC FORCES**Shilpa Vijayakumar¹, Raji M² & Tincy Anna Yohannan³¹PG Scholar, Dept. of Civil Engineering, SVNCE²Asst. Professor, Dept. of Civil Engineering, GECBH³Asst. Professor, Dept. of Civil Engineering, SVNCE

Abstract—Nowadays most of the infrastructure facilities are concentrated towards the underground space due to high rate of global urbanization and increased population. By choosing the underground as a construction space the problems such as greater traffic congestion, higher levels of air pollution, lack of green space and insufficient water supplies etc., can be solved to a great extent. Underground facilities built in areas subject to earthquake activity must withstand both seismic and static loading. Historically, these structures have experienced a lower rate of damage rather than surface structures. But some underground structures have experienced significant damage in recent large earthquakes. The present study deals with 3-D nonlinear finite element analysis of underground twin tunnel subjected to seismic forces by varying parametric sensitivities such as radius of opening of twin tunnels, with and without concrete lining provision and also with varying concrete lining thickness in order to identify the best structural configuration which can adopt in highly earthquake prone areas. Here time-history analysis has been carried out using Kobe earthquake data, in which load is applied in the form of acceleration for analysis. Seismic analysis is carried out by using FEA software package ANSYS v.12, based on elastic and elasto-plastic analysis. The stresses and displacements obtained from analysis on each case have been investigated and compared, which shows the deformation level of the twin tunnels, thereby can identify the better structural configuration with the provision of appropriate spacing.

Keywords: Underground twin tunnel, Elasto-plastic analysis, Kobe earthquake, FEA software ANSYS, Seismic forces

1. INTRODUCTION

The ever-increasing growth of the cities and consequently development of the transportation and communication routes like subway and other underground structures in recent years has lead in especial and extensive studies regarding underground spaces. Underground tunnels are often adopted in urban areas due to a part of urbanization, which results in lack of occupational spaces. Underground facilities have experienced a lower rate of damage rather than surface structures. Nevertheless, some underground structures have experienced significant damage in recent large earthquakes, like the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake. As nowadays for a wide range of lifeline applications, ranging from small pipelines such as those used in natural gas transmission to large underground structures including subway and highway tunnels usually made of reinforced concrete. The importance and cost of large-scale underground reinforced concrete infrastructures make it necessary to analyze the seismic behavior of underground structural system including surrounding soil media accurately. Although the seismic performance of large structures has been extensively studied (e.g. Shawky and Maekawa, 1996, Hashash et al., 2001 and Hu et al., 2005), there have been limited researches regarding the liquefaction-related seismic performance of RC structures. Liu and Song (2005) investigated the dynamic behaviors of a subway station in liquefiable and subjected to horizontal and vertical earthquake excitations. Kimura et al., (1995) conducted some centrifuge model tests to study the effect various countermeasures against liquefaction of sand deposits with an underground structure. In most of these researches, however, the focus was addressed on the behavior of soil itself during seismic motions and the up-lift rigid body motion of berried structures.

Tunnel stability is one of the most important consideration while designing and constructing tunnels. Due to space constraints especially in urban environment, twin tunnels are preferred. Moreover, in the case of structures like tunnels, rather than inertial forces the deformation behavior is controlling the seismic behavior. The various waves generated during an earthquake event generate additional forces and moments, which may jeopardize the stability of underground tunnels. The effects of these seismic forces on underground tunnels mainly depend on type of tunnel lining, tunnel lining thickness or cross-sectional stiffness and its radius of opening. These are the main factors which has to be considered on designing and constructing underground tunnels in a highly earthquake prone areas as it influences the seismic forces. Hence it is necessary to evaluate the performance and stability of underground tunnels under seismic

forces on varying its shape and parametric conditions in order to develop an effective structural feature, which can adopt in highly earthquake prone areas.

In addition to the existing problems in analysis and design of the tunnels under static loading, evidences about the damages of such structures during application of dynamic loads duly reminds the necessity of investigating the dynamic behavior of such underground structures. Hence, nowadays in addition to considering the static conditions in the design of the section and lining of tunnels, identifying the factors involved in the seismic response of such structures and their influence on the structural specifications of the tunnels is of especial importance.

2. STATEMENT OF PROBLEM

In this study, Finite Element Analysis (FEA) of underground twin tunnel subjected to seismic forces is carried out based on elasto-plastic analysis and also evaluating its effect on varying parameters of the tunnel namely shape of tunnel lining, diameter, concrete lining thickness under different earthquake excitation, in order to identify best structural configuration which can suggest in highly earthquake prone areas. Unlike surface structures, soil-structure interaction is very important in the seismic analysis of underground structures. In order to carryout seismic analysis, FEA software package ANSYS v.12 has been used.

In ANSYS, FEA is carried out in three phases mainly preprocessing, solution and post processing phase. Preprocessor phase is for building the model, solution phase is for applying the load and finding the solution, and post processor is for the review of results.

3. THREE DIMENSIONAL FEA MODELING (PREPROCESSING PHASE)

In this study, underground twin tunnels of varying radius 2m, 3m & 4m without and with concrete lining of thickness 350mm & 550mm has been modeled in order to carryout nonlinear seismic analysis using FEA ANSYS software.

The 3-D circular twin tunnels of varying radius 2m, 3m and 4m of 20m, 30m and 40m long is enclosed by soil profiles of cross-section 20mx20m, 30mx30m and 40mx40m respectively of length 20m, 30m and 40m has been modeled without and with concrete lining of thickness 350mm and 550mm for each case. Twin tunnels in each case were spaced at 8m apart. A square plane with twin circular hole has generated. The FE models of the soil and tunnel with concrete lining geometry has been developed with solid65 element which is of higher order version of 3D defined by 8 nodes having three DOF at each node: translations in the nodal x, y and z directions. As the geometry and element type of the models in ANSYS has been set together. The material models and properties assigned to the twin tunnel enclosed with soil profile is shown in table 1 and for the concrete lined twin tunnels is shown in table 2 for both elastic and inelastic cases.

Table- 1 Materials Properties of tunnel enclosed with soil

PROPERTIES	LINEAR ISOTROPIC	DRUCKER-PRAGER
Poisson's ratio	0.25	-
Young's modulus(Pa)	1.25e7	-
Cohesion(Pa)	-	2e5
Friction angle (Degree)	-	30
Flow angle	-	0

Table-2 Material Properties of concrete lined tunnels

PROPERTIES	LINEAR ISOTROPIC	CONCRETELINING
Poisson's ratio	0.2	-
Young's modulus(Pa)	27.4e9	-
Shear stress coefficient	-	0.8
Cracking stress(Pa)	-	3e6
Crushing stress(Pa)	-	30e6

Meshed models have been finally generated by using hexa sweep mesh method for fine meshing. The following figures 1, 2 & 3 shows the final meshed model of circular twin tunnel of varying radius 2m, 3m & 4m spaced at 8m apart enclosed by square soil profile of 20m, 30m and 40m width and depth respectively. Similarly the hexa sweep meshed models of concrete lined twin tunnels with 350mm & 550mm thickness of radius 2m, 3m & 4m were shown in figures 4,5,6,7,8, and 9.

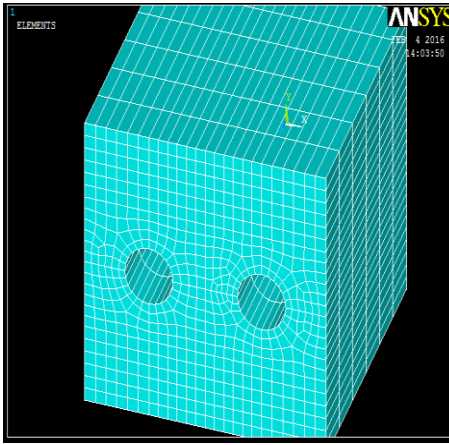


Figure – 1 Meshed model 2m radius

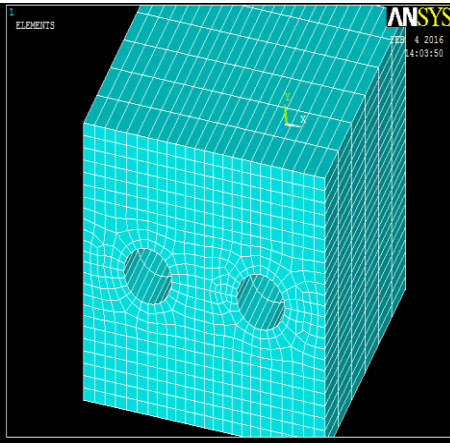


Figure-2 Meshed model 3m radius

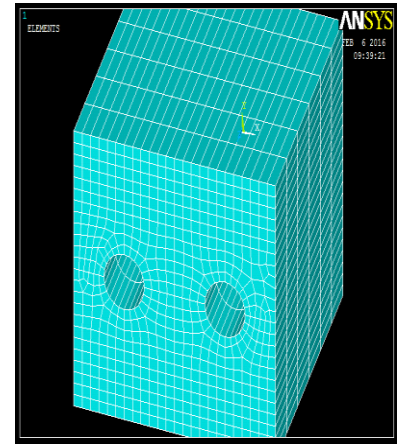
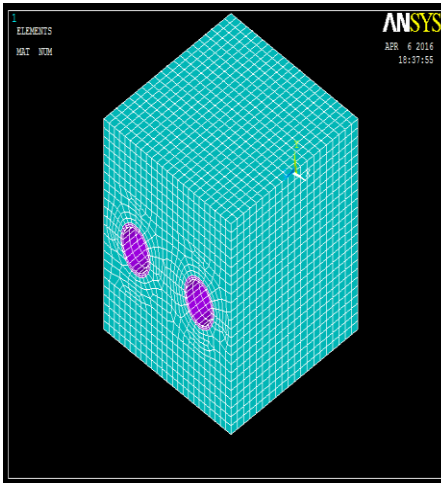
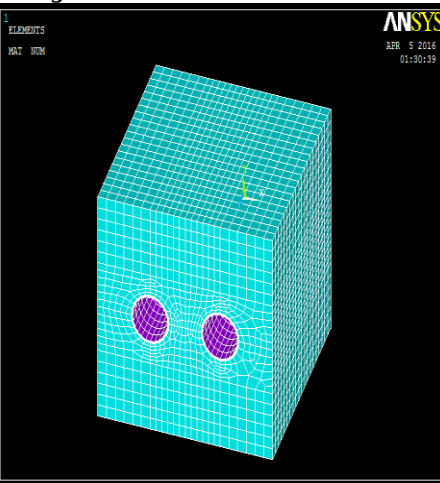


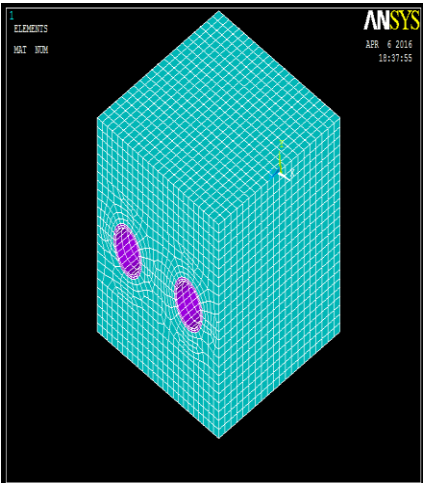
Figure-3 Meshed model 4m radius



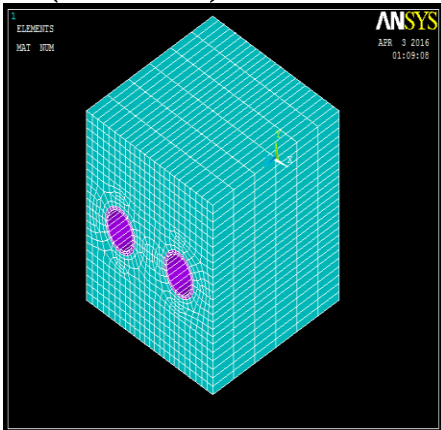
**Figure- 4 Meshed model 2m radius
(Lined 350mm)**



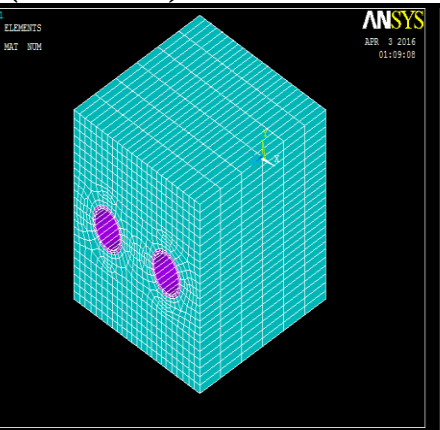
**Figure- 5 Meshed model 3m radius
(Lined 350mm)**



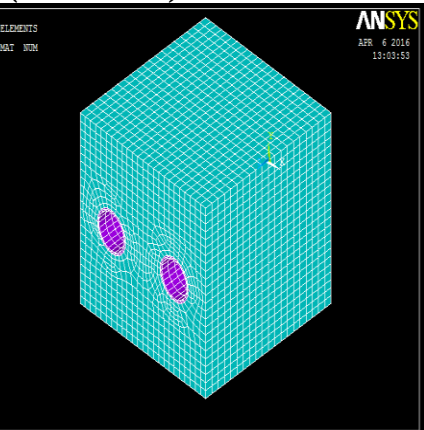
**Figure- 6 Meshed model 4m radius
(Lined 350mm)**



**Figure-7 Meshed model 2m radius
(Lined 550mm)**



**Figure- 8 Meshed model 3m radius
(Lined 550mm)**



**Figure- 9 Meshed model 4m radius
(Lined 550mm)**

4. VALIDATION OF ANSYS v.12 FOR ELASTIC AND ELASTO-PLASTIC ANALYSIS

In order to validate the accuracy of the results derived from ANSYS, and to determine its coherence with existing work, example problems were considered and elastic and elasto-plastic analysis is carried out as follows:

4.1 Validation for Elastic Analysis

One of the proposed models has been used for the validation. A homogenous square plane with a hole, defined as plane 82 element in ANSYS, is used for the analysis. A 2-D underground singletunnel of 3m radius of 30m long is enclosed within a soil profile square plane of 30m. The material model adopted is linear isotropic and the properties assigned are shown on table 3. The meshing of the model has been carried out by using quad free meshed method. For fixity condition, fixed supports were provided on the bottom faces, while the other sides are subjected to uniformly distributed pressure of 10MPa for static analysis. Results obtained from ANSYS were compared with the theory proposed by Kirsch solution (Kirsch, 1898).

Table-3 Material properties used for validation

Density	Poisson's ratio	Young's modulus
1800kg/m ³	0.3	1.25e7 Pa

The radial / tangential stress obtained from ANSYS and Kirsch solution are compared and found to be approximately identical, as shown in figure 10. The comparison of the model shows that the results obtained are in good agreement with the Kirsch's theoretical solution. The superimposition of the graph validates this elastic analysis in ANSYS.

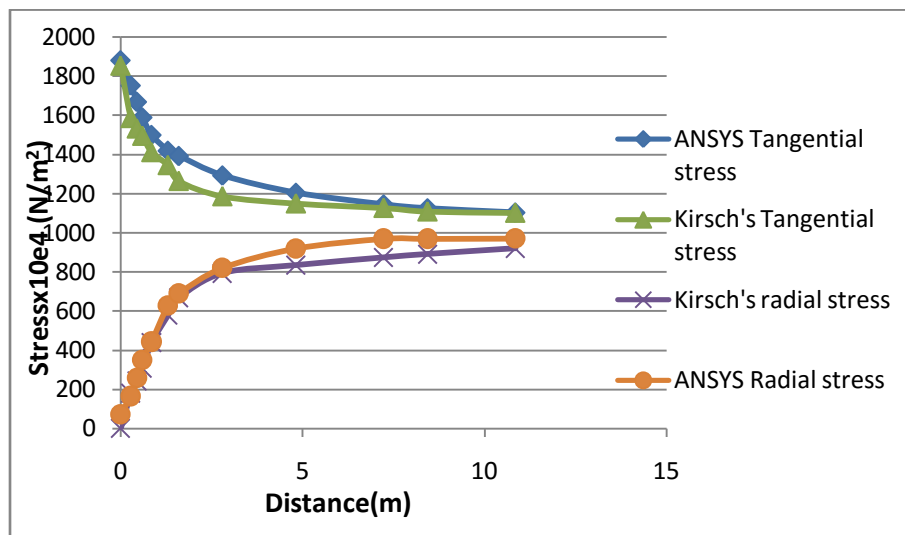


Figure-10 Graphical comparison of the results from Kirsch's solution vs ANSYS

4.2 Validation for Elasto-Plastic Analysis

For elasto-plastic analysis, model with same geometry, element type, meshing and loading conditions has applied except for material properties. Here Drucker – Prager model of ANSYS is selected for obtaining inelastic behavior of the tunnel and linear isotropic for linearity behavior. Formation of both elastic and plastic zone occurs when the stress developed exceeds the yield strength. Using the Drucker-Prager model in ANSYS, the results were compared with solutions obtained from the theoretical model propositions of Bray solution (Bray, 1967). The material properties used for the model is shown in table-4. The stresses obtained in the inelastic analysis of the FEA ANSYS model is shown in figure-11 along radial and tangential directions.

Table-4 Material properties used for validation

Density	Poisson's ratio	Young's modulus	Internal Friction Angle	Cohesion	Dilatancy angle
1800kg/m ³	0.3	1.25e7 Pa	30 deg:	2e5 Pa	0

The graphical comparison of the stresses obtained from ANSYS FEA model and the Bray's analytical solution along tangential and radial direction verifies the capability of the finite element tool and confirms that the Drucker-Prager model in ANSYS is an appropriate tool to analyze the elastic and plastic stresses and model the deformations. The deviation observed is attributed to the difference in choices, with respect to initial plasticity zone, and meshing adopted for the finite element model.

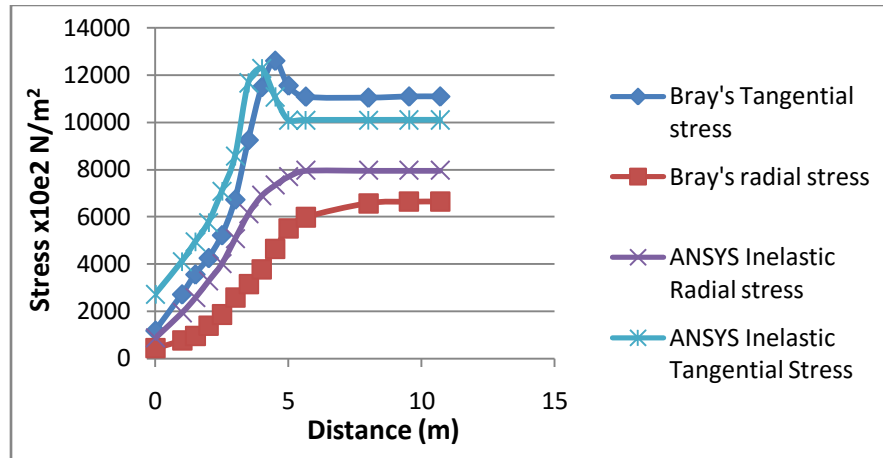


Figure-11 Graphical comparison of the results from Bray's solution vs ANSYS

5. ANALYSIS OF UNDERGROUND TWIN TUNNEL FOR EARTHQUAKE INDUCED DAMAGE

It is the final stage of finite element analysis of underground twin tunnel which involves solution and post processor phase. In which seismic analysis of circular twin tunnels have been performed for its varying parametric sensitivities. Time history analysis has been carried for seismic performance using Kobe earthquake data (1995). Here load is applied in the form of acceleration for duration of 60 seconds with time interval 0.01 seconds. Seismic load is applied uniformly distributed along the outer face in X-direction as gravity load. The effect of improper boundary conditions may affect the analysis to a great extent. Therefore in this study, for fixity condition the bottom face of the tunnel is fixed while the side faces are provided with roller support ie; lateral displacements were arrested.

As the seismic analysis have been conducted for 9 models of underground twin tunnels with 2m, 3m & 4m radius without and with varying concrete lining 350mm and 550mm. Analysis has been completed for 60 seconds, as the 9 models took the whole load and the solution is obtained. The maximum stress and displacement induced by the seismic load in each model is studied and observed in order to evaluate the deformation level and to identify the structural configuration which shows better stability and integrity. In this study, maximum principle stresses and total displacements induced in the tunnels were plotted to evaluate its deformation levels. The stress and displacements contours of the twin tunnels in case are shown in the following figures.

Variation of Principle Stresses of twin tunnel with varying parametric sensitivities

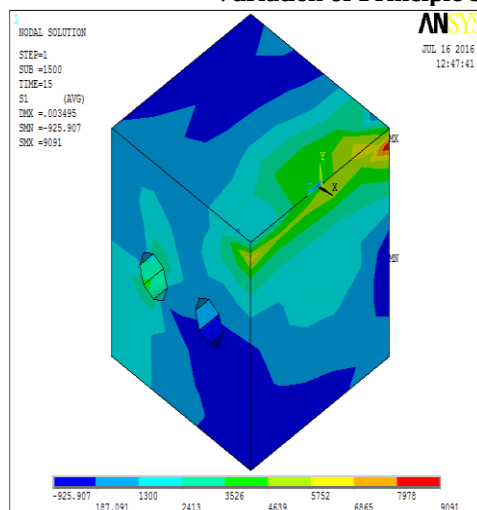


Fig-12 2m radius twin tunnel

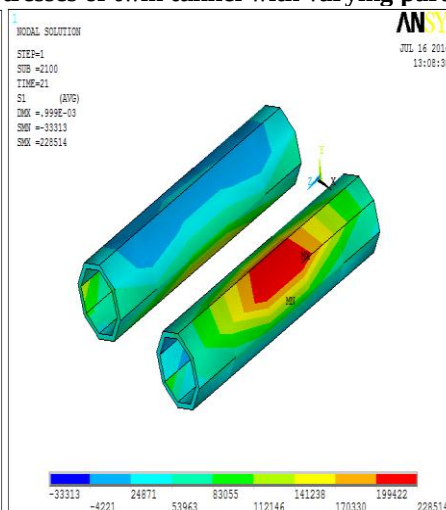


Fig-13 2m radius with 350mm lining

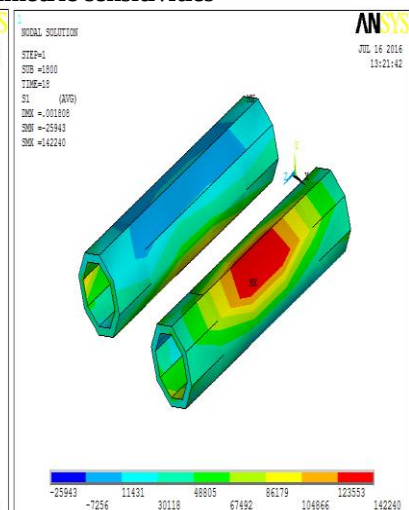


Fig-14 2m radius with 550mm lining

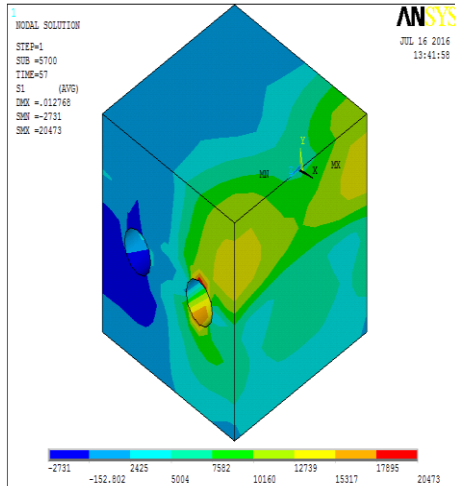


Fig-15 3m radius twin tunnel

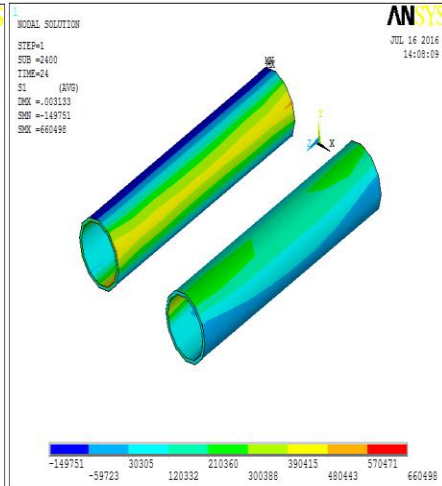


Fig-16 3m radius with 350mm lining

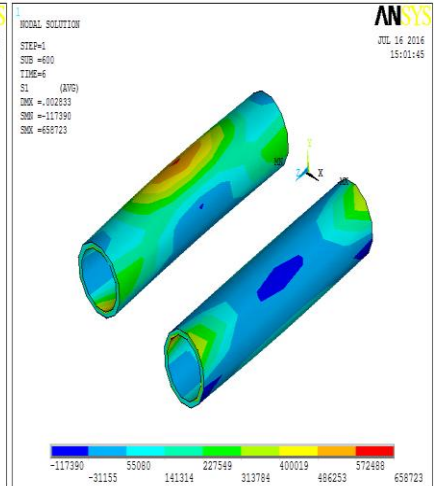


Fig-17 3m radius with 550mm lining

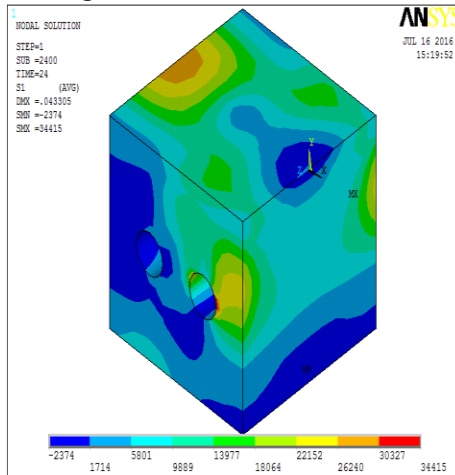


Fig-18 4m radius twin tunnel

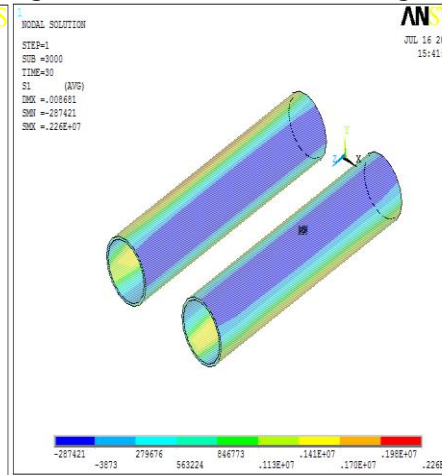


Fig-19 4m radius with 350mm lining

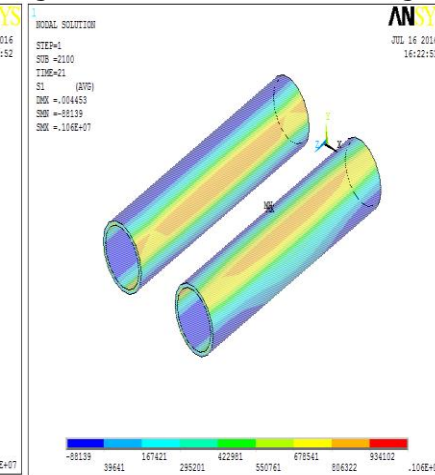


Fig-20 4m radius with 550mm

Variation of Total displacements of twin tunnel with varying parametric sensitivities

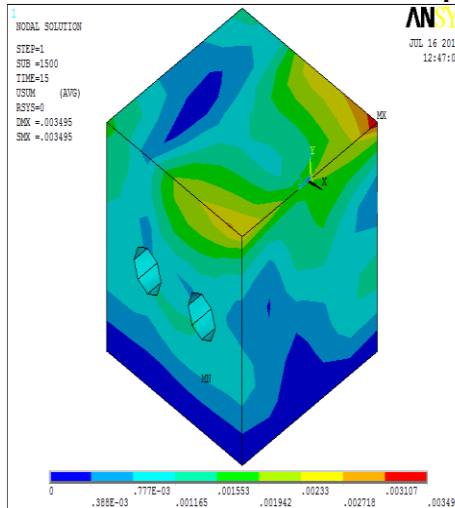


Fig-21 2m radius twin tunnel

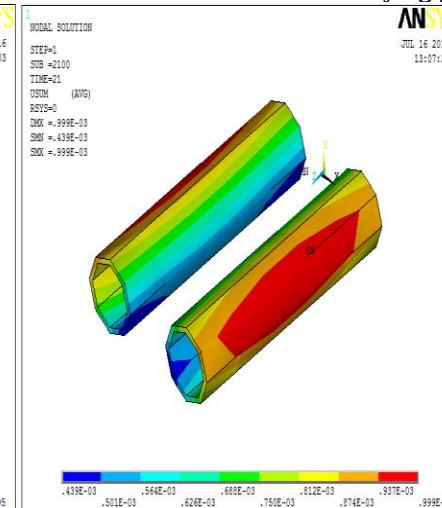


Fig-22 2m radius with 350mm

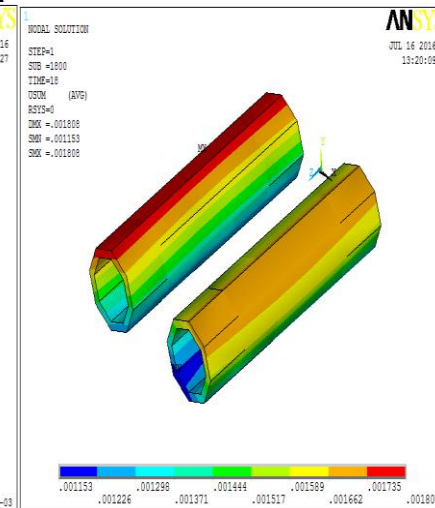


Fig-23 2m radius with 550mm

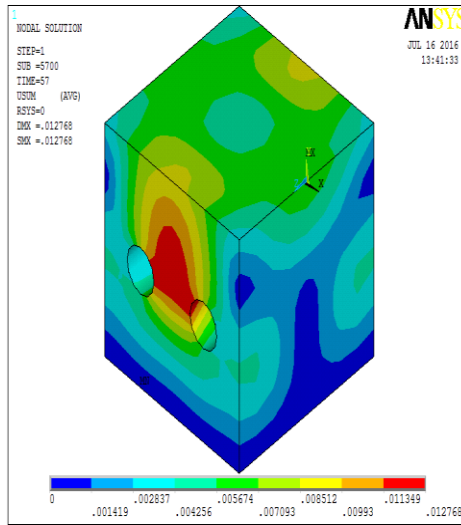


Fig-24 3m radius twin tunnel

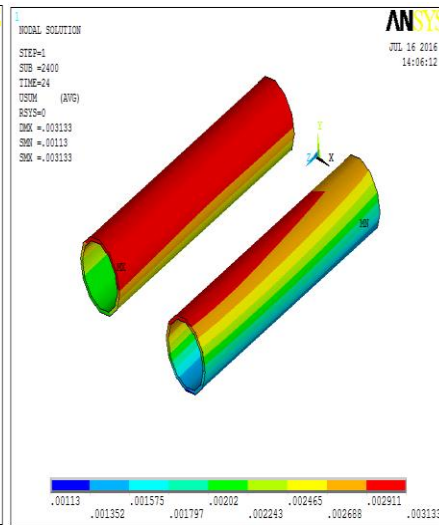


Fig-25 3m radius with 350mm

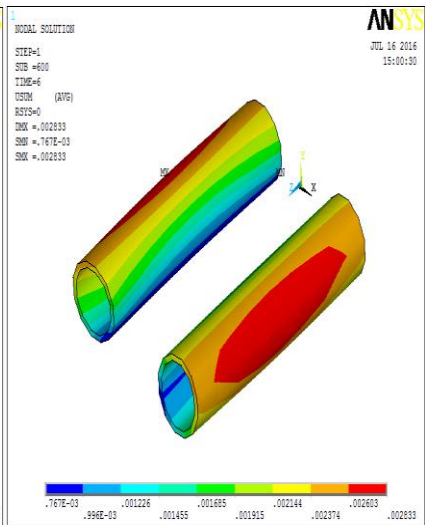


Fig-26 3m radius with 550mm

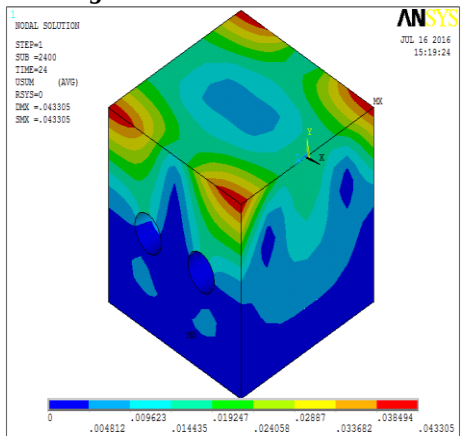


Fig-27 4m radius twin tunnel

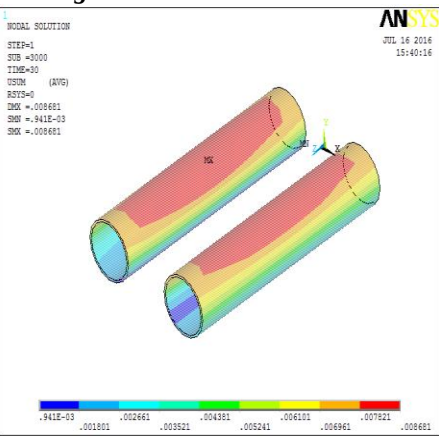


Fig-28 4m radius with 350mm

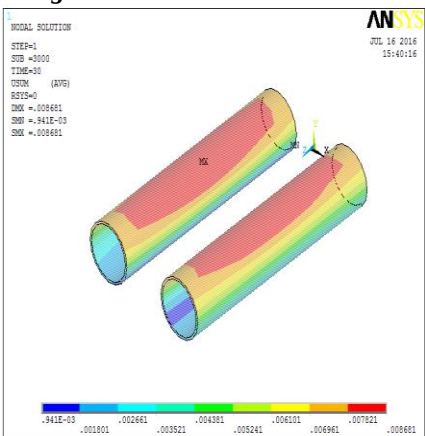


Fig-29 4m radius with 550mm

6. RESULTS AND DISCUSSION OF PARAMETRIC STUDIES

Parametric sensitive studies of an underground twin tunnel subjected to seismic forces has been carried out for (a) varying radius (b) with and without concrete lining and (c) varying concrete lining thickness. The estimation of stresses and displacements around the tunnel due to earthquake loading requires special attention as it has a major influence on the design of lining and prediction of stability.

6.1 Variation of tunnel radius without lining

The stresses and displacements generated by 2m, 3m & 4m radius twin tunnel subjected to seismic forces have been carried out. Stress contours shows that, in and around the opening of tunnel, stress values are much higher as away from the opening its found to be lower value. Maximum stress is concentrated within the periphery of excavated tunnel mainly at crown and sidewalls of tunnel. Whereas in case of displacement, maximum displacements are found at the corner portions of the tunnel profile and along the length of tunnel. Comparison study shows that among 2m, 3m and 4m radius twin tunnel without lining, 4m radius tunnel exhibits maximum stress and displacements as compared to other ones. Hence stress concentration over tunnel and displacements in the soil profile due to seismic loading, increases with increase in the radius of opening of tunnel. Hence structure with minimum radius of opening exhibits maximum structural integrity and performance under seismic performance.

Table-5 Results of twin tunnels without lining under seismic loading

RESULTS	2M	3M	4M
Time (seconds)	15	57	24
Max: Displacement (m)	0.003495	0.012768	0.043305
Max: Principle stress (N/m ²)	0.909e4	0.204e5	0.344e5
Max: Stress intensity (N/m ²)	0.97e4	0.18e5	0.33e5

6.2 Variation of tunnel radius with varying cross-sectional stiffness

The stresses and displacements generated by 2m, 3m and 4m radius twin tunnel with 350mm and 550mm lining thickness subjected to seismic forces has been carried out. Stress contours shows that the maximum stress get concentrated at the mid-span of the tunnel, as lower stresses get distributed to both sides from the mid. As stress distribution pattern and the maximum stress concentration location are found to be same in both cases with 350mm and 550mm lined tunnels of varying radius but its stress intensity and deformation level varies. Whereas in case of displacement, Maximum displacement occurs along the length of tunnel in each case but the degree of displacement varies. Higher displacement is found for lined tunnel with 350mm rather than 550mm thickness. The negative and positive displacement in the contour signifies the tension and compression, as tunnel crown moves downward and the sidewall moves inward. Comparison shows that lined tunnel with 2m radius 550mm concrete lining exhibits minimum stresses and displacements as compared to other models, which shows minimum deformation under seismic loading. As the deformation of the underground tunnel decreases with increased tunnel lining thickness and with minimum radius of opening.

Table-6 Results of twin tunnel with varying lining thickness under seismic loading

RESULTS	2M 350MM	2M 550MM	3M 350MM	3M 550MM	4M 350MM	4M 550MM
Time (seconds)	21	18	24	6	30	21
Max: Displacement(m)	0.000999	0.0001808	0.003133	0.002833	0.008681	0.004453
Max: Principle stress (Pa)	0.228e6	0.142e6	0.660e6	0.658e6	0.226e7	0.106e7
Max: Stress intensity	0.242e6	0.150e6	0.760e6	0.731e6	0.241e7	0.109e7

6.3 Variation of tunnel radius without and with concrete lining thickness

The results of seismic analysis in which stresses and displacements of underground twin tunnels of varying radius without and with lining were observed and compared. By considering the twin tunnels with and without lining of varying radius, found that tunnels with no lining exhibits higher stresses and displacements as compared to tunnels with lining exhibits about 75% higher, with higher radius of opening. It shows that the structure results maximum deformation under seismic loading. Thereby comparing among lined tunnels, tunnel with higher concrete lining (550) exhibits minimum displacement and stresses, as it possess good stable configuration as compared to 350mm lined tunnel. From all which, it clearly shows that the structure with minimum radius of opening and with concrete lining of higher thickness exhibits good performance under FEA subjected to seismic loading as compared to other structural configuration. Maximum influence zone for displacement and stress were found for tunnel with no lining and higher radius of opening. The following are the figures which show the comparison of stresses and displacements developed by each underground twin tunnel with varying parameters.

Principle stress

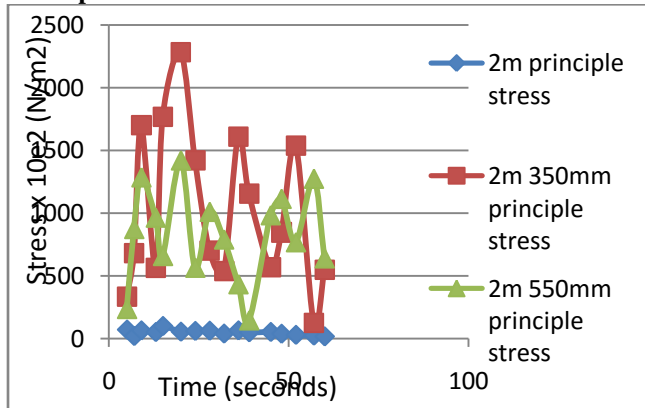


Fig-30 Principle stress vs Time graph for 2m radius

Displacement

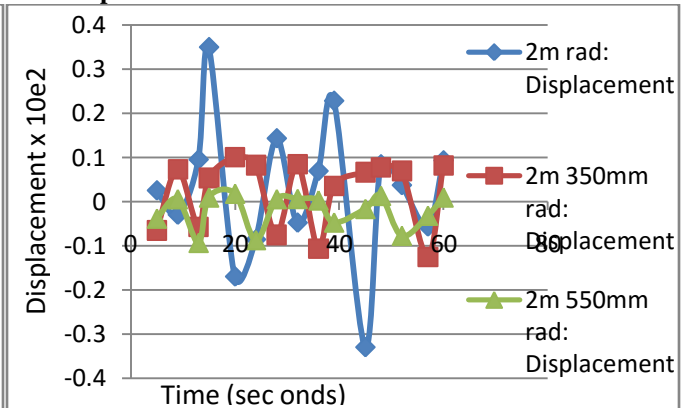


Fig-31 Displacement vs Time graph for 2m radius

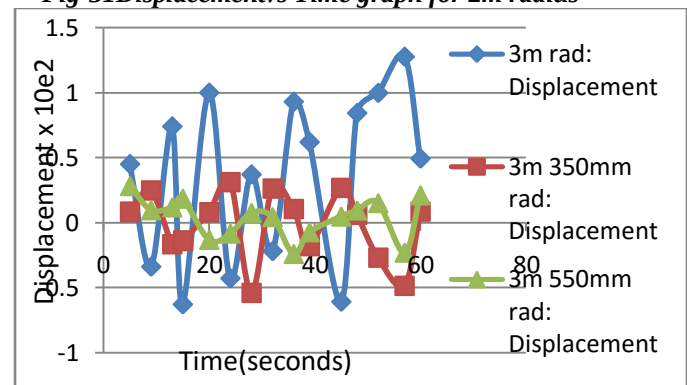
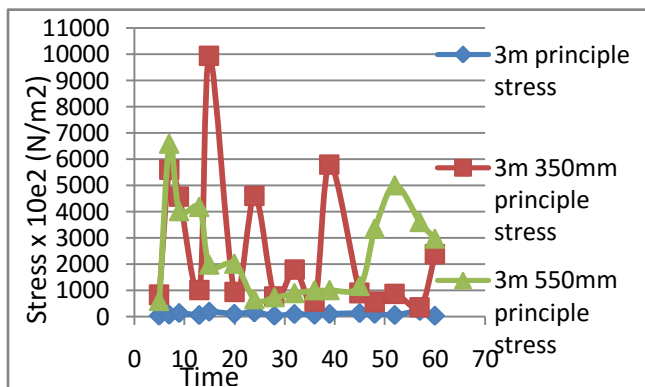


Fig-32 Principle stress vs Time graph for 3m radius
Fig-33 Displacement vs Time graph for 3m radius

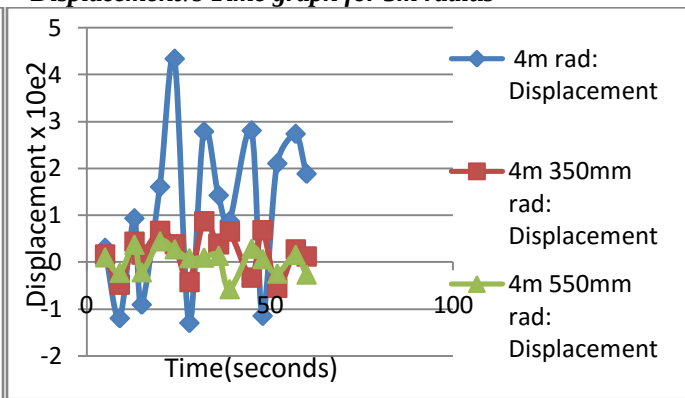
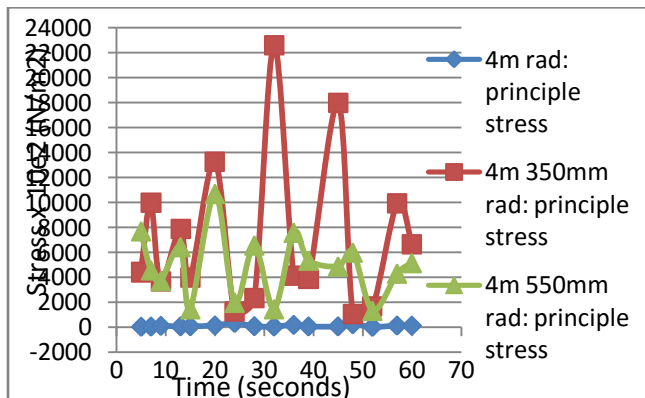


Fig-34 Principle stress vs Time for 4m radius

Fig-35 Displacements vs Time graph for 3m radius

7. CONCLUSION

In this study, full elasto-plastic nonlinear transient analyses of underground twin tunnel subjected to seismic forces have been carried out. As underground structures are an integral part of infrastructure of modern society in urban areas and they are prone to only seismic forces. Hence it is necessary to evaluate the performance of these structures under distinct earthquake forces in order to set new guidelines for the design phase. For time history analysis, Kobe earthquake data has been used in this study. Parametric sensitivity studies have been performed for (i) varying radius (ii) concrete lining thickness (iii) earthquake intensities. The stresses and displacements, which lead to deformation of twin tunnels caused by seismic loading on varying parameters, are investigated. The simulation of the present problem has successfully carried out in ANSYS v.12 and the parametric studies concluded that the structure with minimum radius of opening with higher concrete lining thickness having appropriate spacing between the tunnels exhibits minimum stresses and displacements lead to better stable

configuration as compared to structures having higher radius of opening and without lining. By the provision of appropriate spacing, the stress interference effects get negligible.

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