E-ISSN 2581 – 7957
P-ISSN 2277 – 3916

CVR Journal of Science and Technology, Volume 21, December 2021
DOI: 10.32377/cvrjst2103

Seismic Analysis of Underground Reinforced Concrete Highway Tunnels with Different Shape Openings using Curved Arch Concept

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Abstract: **A tunnel is an underground passageway, dug through the surrounding soil/earth/rock and enclosed except for entrance and exit, commonly at each end. Now-a-days, tunnels are being used for many purposes like roadway, railway tracks, for canal etc. Tunnels help in reducing the distance between any two places. In this research work, Seismic analysis of tunnel was carried out for different shape openings of tunnel using curved arch concept. The design and analysis work has been carried out using SAP-2000 package. Analysis of different type of tunnels for seismic loading is done for the variation of the stresses, moments and displacements. Same process was followed for the tunnel shapes and based on results; the best and stronger tunnel is specified. This paper mainly concentrates on the variation of displacements and stresses under static loading conditions and efficiency under static loads.**

Index Terms: **Underground tunnels, response of structure, design and analysis, displacements, stresses, SAP-2000**

I. Introduction

Seismic analysis of tunnels is important for safety evaluation of the tunnel structure during earthquakes. Simplified models of tunnels are commonly adopted in seismic design by practitioners, in which the tunnel is usually assumed as a beam supported by the ground. These models are made to run in real time to give a virtual response close to the actual system. However, simplified methods are limited due to the assumptions that need to be made to reach the solution, e.g., shield tunnels are assembled with segments and bolts to make a lining ring and such structural details might not be included within the simplified model.

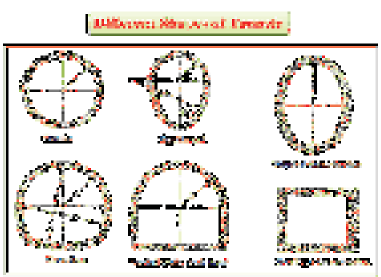

Figure 1. Different shapes of tunnel

A reliable evaluation of the seismic response of tunnel structures is crucial in civil and earthquake engineering. As the structural design has shifted to the performance design in recent years, the seismic design, accounting for the soil–structure interaction (SSI) effects, becomes more important. The presence of a tunnel structure considerably modifies the free field ground motion leading to a different seismic response of the tunnel lining. This phenomenon is related to the combined effects of the kinematic interaction and the dynamic (inertial) interaction. The kinematic interaction is influenced by the inability of a structure to match the free field deformation. The dynamic interaction is caused by the existence of a structural mass making the effect of inertial force on the response of the surrounding environment, in which case dynamic forces in the tunnel's structure cause the tunnel to deform the soil, thus producing stress waves that travel away from the structure (radiation damping).

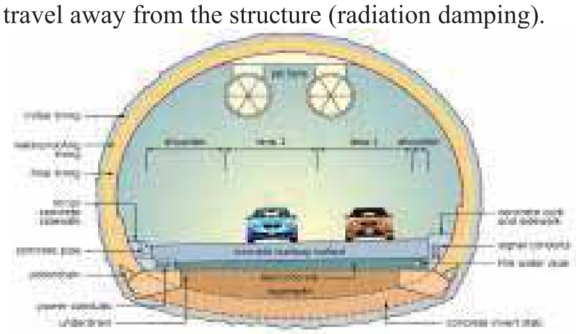

Figure 2. Cross-sectional view of a general tunnel

A. Objectives:

- To study the variation of stresses, moments and displacements of the tunnel.
- To compare the variations of structure parameters analyzed using SAP-2000.
- To verify that which cross section is more efficient and strongest.
- To suggest the improvements and remedies.

B. Scope:

In the static analysis of tunnel pore water pressure can also be considered and carry the analysis by applying the pore water pressure all over the tunnel slab.

II. Literature Review

Seismic Damage Analysis of Box Metro Tunnels Accounting for Aspect Ratio and Shear failure by Duy-Duan Nguyen, Tae-Hyung Lee, Van-Quang Nguyen and Duhee Park**.** In this paper they performed a series of inelastic frame analysis for single, double and triple concrete

Received on 28-08-2021, Revised on 23-10-2021, Accepted on 22-11-2021.

reinforced box tunnel focus mainly on the influence of aspect ratio of box tunnels and shear structural failure. Here, flexural failure is considered with an aspect ratio of 1 for the damage analysis of box tunnels. As per their analysis only flexural failures occurs in single box tunnels, whereas for double and triple box tunnels shear structural failures occurs at the inner column. structural collapse is not found for single box tunnels. It is also proved that the increase in the aspect ratio leads to increase in the seismic resistance. It is also proposed revised damage indices (DIs) corresponding to three damage states for single box tunnels. Here, DI is the ratio of elastic moment to yield moment.[1]

Finite Element Seismic Analysis of Cylindrical Tunnel in Sandy Soils with Consideration of Soil-Tunnel Interaction by M. Saleh Asheghabadi and H. Matinmanesh, Department of civil engineering, Islamic Azad University, Njafabad branch, Isfahan, Iran. Distribution of Seismic waves from the bedrock through the soil layers can cause severe damages to the structures not only on the soil surface but also to subsurface structures. This paper presents an idealized two-dimensional plain strain finite element seismic soil-tunnel interaction analysis using ABAQUS v.6.8 program. The analysis performed by considering three actual ground motion records representing seismic motions with low, intermediate, and high frequency content. Two different sandy soils i,e. dense and loose sand have been modelled. In order to consider the effect of soil-tunnel interaction, all of the analysis was performed for without tunnel condition and compared with models including tunnel. Influence of different subsoil's dense and loose sand in each actual ground motion record has been investigated on amplification, acceleration response and stress and strain propagation on the soil-tunnel interface. Results illustrate that existence of tunnel amplifies the seismic waves on the soil surface and the maximum amplification occurs on the interface of the tunnel and soil.[2]

Seismic analysis of dynamic structure-soil-tunnel interaction for a case of the Thessaloniki Metro by D. Lončarević, E. Bilotta & F. Silvestri, University of Naples Federico II, Naples, Italy; G. Tsinidis University of Sannio, Benevento, Italy. This paper studies the dynamic interaction between an underground metro station and a building with basement which are at a distance. This paper studies, the effect of building on the metro station when subjected to seismic excitation in the transversal direction. They have considered a real case study of metro station in Thessaloniki, Greece. This metro structure is analyzed under plain strain conditions using ABAQUS software and the building is simulated as an equivalent single degree of freedom oscillator. The results obtained by this analysis are compared with the results obtained by the analysis of underground structure without considering the building aside. By this comparison, we can identify and quantify the effects of the dynamic interaction between the structures on the racking response of the station. The analytical result indicates a general increase of seismic response of the station due to the presence of the building.[3]

Numerical Modeling of the transverse dynamic behavior of circular tunnels in clayey soils by A. Amorosi, D. Boldini. In this paper, they went with different approaches aimed at investigating the dynamic behavior of circular tunnels in transverse direction. Cases referring to a shallow tunnel built in two different clayey soils are analyzed. The adopted approach includes 1D numerical analysis performed modelling the soil as a single phase visco-elastic non-linear medium, the results of which were then used to evaluate the input data for selected analytical solutions proposed in the literature, and 2D fully coupled FE simulations adopting visco-elastic and visco-elasto-plastic effective stress models for the soil. The results were proposed in terms of seismic-induced loads in the transverse direction of the tunnel lining. Particularly the plasticity-based analysis indicates that a seismic event can produce a substantial modification of loads acting on the lining, leading to permanent increments of both hoop pressure/force and bending moment.[4].

III. METHODOLOGY

1) In this study analysis of tunnels with different shape openings was carried out using SAP-2000.
2) Some dimensions for tunnel shapes with the reference of some standard journals are taken into consideration.
3) And also, the specifications for seismic load application.
4) A grid is created with required dimensions.
5) With that grid and dimensions, tunnel shapes in SAP-2000 are modelled.
6) After the shapes were modeled, define materials i.e., soil details which is to be applied on the tunnel.
7) Now define the load cases i.e., soil and earthquake load in X-direction.
8) Fix the joints which are at the bottom of the tunnel and in contact with the soil.
9) The load coming on to the tunnel from above is soil pressure.
10) Loads coming from sides are known as active earth pressure.
11) Calculate the soil loads from top and active earth pressures.
12) Apply the loads calculated at the respective joints.
13) Define a diaphragm in the joint constraints.
14) Now all set to go for seismic analysis of tunnel.
15) Now run the analysis program and note down the results.
16) Take out the displacement values of the tunnels, stresses and moments also.
17) Study the obtained results and make a conclusion.
18) Suggest remedy measures needed.

IV. CALCULATION OF LOADS ACTING ON THE TUNNEL

In this research I considered a 3m soil layer on the tunnel. And net weight of soil is 20KN/m^2. Tunnel is covered with soil on all sides which act as a backfill of a retaining wall. So, here active earth pressure is also acting on the tunnel, and on the slab total soil load will act. Below is the clear picture of loads acting on the tunnel.

Active earth pressure coefficient, $K_a = 1/3$

Passive earth pressure coefficient, $K_p = 3$

Forces coming onto the tunnel by the soil layer can be calculated as below.

Earth pressure acting on slab, $\sigma = \rho gH = \gamma H$ (KN/m^2)

Active earth pressure acting on retaining wall,

$\sigma_a = K_a\rho gH = K_a\gamma H$ (KN/m^2)

Load acting on the slab, σ = 20*3 = 60 KN/m^2

So, the total load acting on the slab = 60*(8*30) = 14,400 KN

Now coming to the loads on the side slabs or retaining walls, as we go down or deeper from the top of the soil surface the active earth pressure acting on the walls get increasing. That variation of loads is as shown below. And variation of loads is same on both sides as the tunnel is symmetric. Depth "**H**'' is from top of the soil layer.

At 3m, $\sigma_{a\,=}$ 1/3*20*3 = 20 KN/m^2

At 4m, $\sigma_{a\,=}$ 1/3*20*4 = 26.67 KN/m^2

At 5m, $\sigma_{a\,=}$ 1/3*20*5 = 33.33 KN/m^2

At 6m, $\sigma_{a\,=}$ 1/3*20*6 = 40 KN/m^2

At 7m, $\sigma_{a\,=}$ 1/3*20*7 = 46.67 KN/m^2

At 8m, $\sigma_{a\,=}$ 1/3*20*8 = 53.33 KN/m^2

At 9m, $\sigma_{a\,=}$ 1/3*20*9 = 60 KN/m^2

At 10m, $\sigma_{a\,=}$ 1/3*20*10 = 66.67 KN/m^2

At 11m, $\sigma_{a\,=}$ 1/3*20*11 = 73.33 KN/m^2

V. Analytical Study

To achieve same height for all the tunnels, base width must vary from tunnel to tunnel. Make sure that height of all tunnels is same. Then, modeling of tunnel shapes using the finite element software can be done. Use SAP-2000 for modeling and analysis. Dimensions are mentioned as below,

Height of the tunnel - 8m

Length of the tunnel - 30m

Width of the tunnel - varies from shape to shape

After taking the dimensions, note concrete grade, steel specifications and also tunnel lining thickness.

Thickness of tunnel lining – 0.3m

Grade of concrete – M50

Grade of steel – HYSD 415

No of layers of reinforcement – 2

Diameter of steel – 20d

Clear cover – 50mm

After completing the modeling part soil data from some journals is collected.

Thickness of soil layer above the tunnel – 3m

Type of soil – type II (medium hard clay soil)

Soil properties:

Weight per unit volume of soil=20 KN/m^3

Poisson ratio = 0.3

Modulus of elasticity, E = 65000 N/m^2

Cohesion, C = 3

Friction angle, $\phi = 30^0$

From the above the tunnel, the load is soil load which directly acts vertically downwards on the tunnel. And the soil load coming from sides is Active earth pressure (P_a). Calculate the earth pressures at every joint corresponding to their height from the top of the soil surface.

Soil pressure of soil on the slab of tunnel, P = γ*H

Active earth pressure, $P_{a\,=}$ 1/3 *γ*H

Here, γ = unit weight of soil

H = depth of the respected joint from the soil layer surface above the tunnel

Calculate the loads at the points considered. Now follow the procedure for specifying soil data, fixing the bottom joints with the soil, defining load cases, load application and applying diaphragm.

- ➔ Define – Materials – Add new material – Reg ion & material type – give soil details – ok (material defined)

  After defining the material properties, we need to define the load patterns.
- ➔ Define – load patterns – define soil & earthquake loads – give earthquake load specifications – ok (load patterns are defined)
- ➔ For the application of earthquake load the specifications considered for this study are:
- ➔ IS code 1893-2002 (part 1)
- ➔ Seismic zone – II
- ➔ Seismic zone factor, Z – 0.1(Hyderabad)
- ➔ Importance factor, I – 1.5
- ➔ Soil type – II
- ➔ Select joints to be fixed – go to Assign – joints – Restraints - Fixed – ok.
- ➔ Select joints on which loads to be applied – Assign – joint load – forces – select Soil load – give loads – ok.
- ➔ Select area of loading – Assign – Area loads – Uniform (shell) – Soil load – enter load amount – ok.
- ➔ Select all the joints – Assign – Joint – Constraints – Define joint constraint – Diaphragm – ok.

Now it's all set for analysis of tunnel structure. Confirm all the loads, diaphragms etc., once again. Then Run the analysis. The deformed shape of the structure will show up. Go to display command and set deformed shape with contours, moment diagrams with values, stress diagrams with contours and values, displacement contour and axial force variation with values.

Using the above data, the tunnel modeling in SAP-2000 is done. And those models are as shown below with cross section view and three-dimensional view.

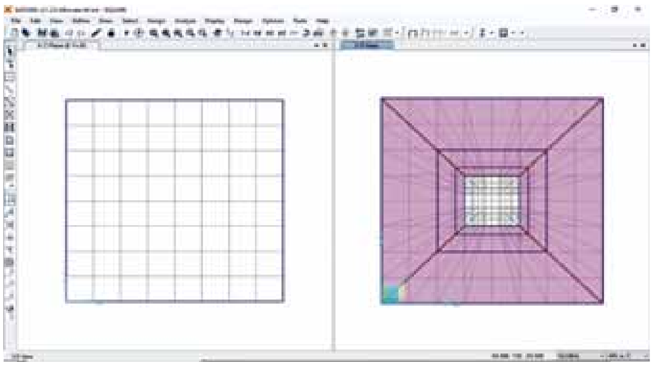

Figure 3. Square tunnel cross-section

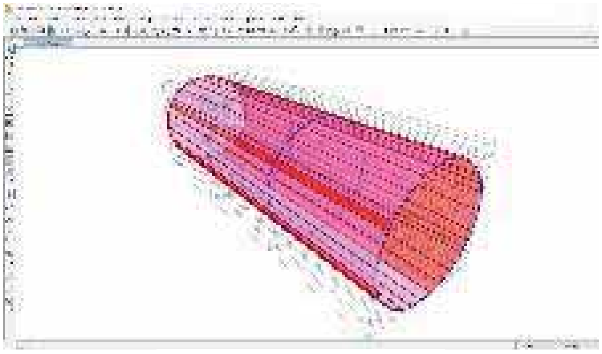

Figure 4. Circular tunnel-3D view

Similarly the Rectangular, Semi-circular, 3/4th circular, Vertical walls-arch roof, Vertical walls-semi circular arch and elliptical tunnel shapes are designed.

VI. Results and Discussions

The analysis carried out was linear static analysis. After running the analysis, the results of deformation, moments and stress variations with their diagrams and contours are obtained as shown below.

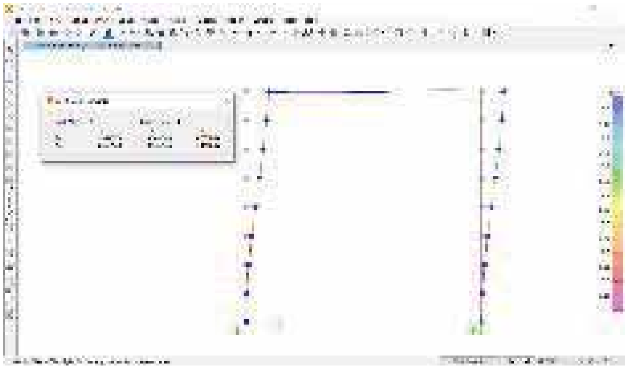

Figure 5. Square Tunnel - Deformed shape

As seen from **Figure 5** the deflection curve of Square tunnel from origin means base point and there is an increment in the deflection of the curve. Consider earthquake wave in X-direction, tunnel lean towards positive X-axis. Deflection at base is 0 and max deflection at the top is 7.8mm.

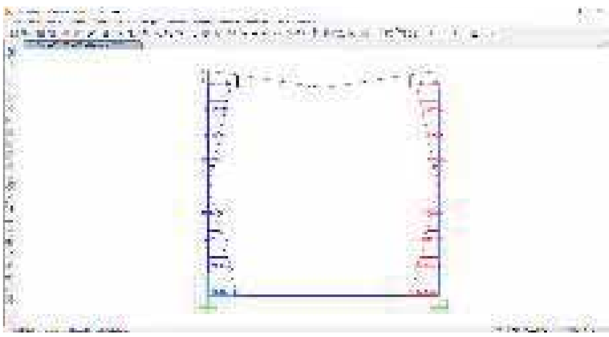

Figure 6. Square Tunnel - Stress variation values

As seen from **Figure 6** stress diagram, on left side stress value is max at the fixed base. We go up stress gets reduced and become min at midpoint and again increasing from there to top. Positive stress indicates tension force. So left half of the tunnel subjected to tension during earthquake load. On the right half of tunnel from bottom to top stresses are negative.

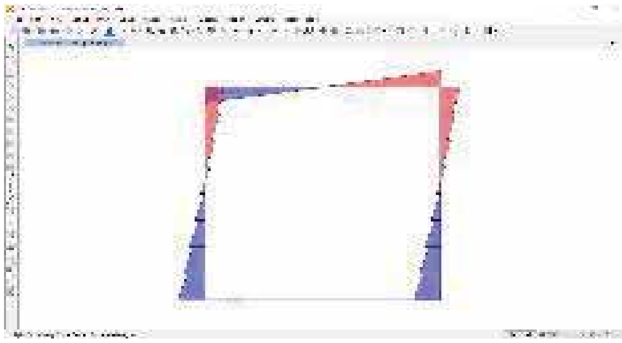

Figure 7. Square Tunnel – moment diagram

Positive (+ve) moment indicates sagging and negative(-ve) moment indicates hogging of the curve. So, from **Figure 7** we can observe, on left side at base moment is max. The moment gets reduced and changes its sign and become –ve in the upper part of the curve. That point is known as point of **contra flexure**. Negative moments are continued up to top and become max. That –ve moments indicates happening of hogging. Coming to the slab part from left to right sagging (+ve moments) and hogging (-ve) can be observed. Right flank is similar to left one, same moment variation can be observed.

TABLE I.
Results Obtained From Analysis– Square Tunnel

Ht. from base(m)	Deformation (mm)	Moment (KN-m)	Stress (KN/m^2)
0	0	15.39	3429
1	3	12.14	2282.38
2	10	8.88	1570.18
3	21	5.63	801.28
4	34	2	135.51
5	47	-2.72	634.77
6	60	-5.6	1301.58
7	70	-8.24	1863
8	78	10.56&985	-2190.26
8	78	-9.85&-10.56	-2203
7	70	-8.24	-1712.86
6	60	-5.6	-908.3
5	47	-2.72	-254.74
4	34	2	-590.89
3	21	5.63	-1277.8
2	10	8.88	-2022.14
1	3	12.14	-2933.29
0	0	15.39	-3429.48

DOI: 10.32377/cvrjst2103

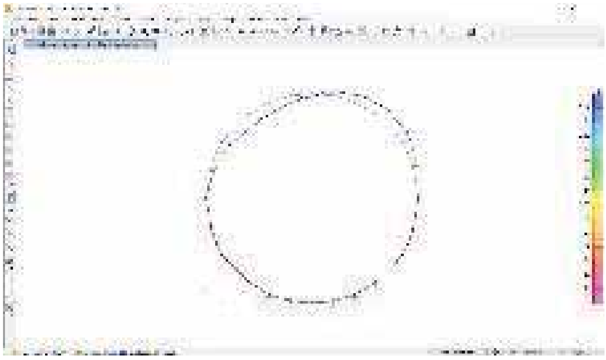

Figure 8. Circular Tunnel – Deformed shape

From **Figure 8**, deflection variation of tunnel can be observed. Some of the base joints are fixed which are having no deflection. After fixed joints deflection increases from the base. The deflection at the top joint is 0. And same deflection variation can be seen on the right half of the tunnel. Max deflection is 0.3mm at 6m from base.

Figure 9 is stress variation diagram of circular tunnel. Coming to stress variation Left half has +ve stresses and it is pure tension. Max stress is at bottom and min stress 90km/m2 is at top. Similarly, on the fright side stresses are – ve from middle to bottom. It indicates compression at the bottom only.

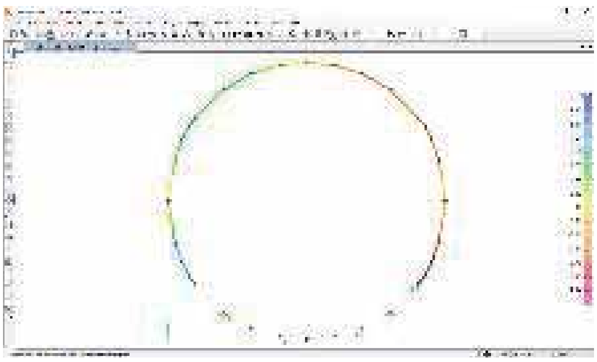

Figure 9. Circular tunnel - Stress contour

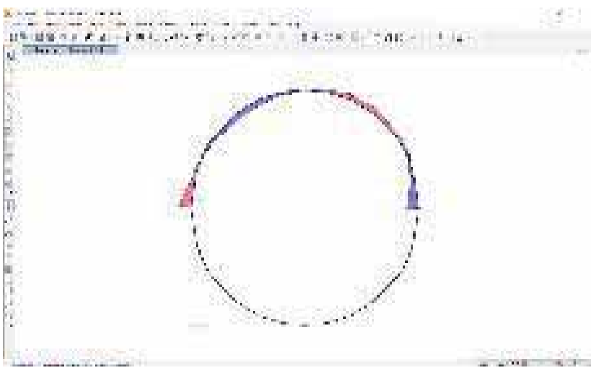

Figure 10. Circular tunnel – moment variation diagram

Figure 10 is moment variation diagram. It is clear that moments are much less at left bottom side after fixed joints. And become 0 at mid height. Again, increases and become max at 3/4th of height from bottom and gets decreased further and becomes 0 at the topmost point. These positive moments show that tunnel undergoes sagging on left. On right half stresses are –ve means tunnel undergoes hogging.

TABLE II.
RESULTS OBTAINED FROM ANALYSIS – CIRCULAR TUNNEL

Ht. from base(m)	**Deformation(mm)**	**Moment (KN-m)**		**Stress (KN/m^2)**	
0	0	5.77	-5.77	1319.95	1313.85
0.3	0	5.16	-5.16	1188	1172.3
0.8	0	4.23	-4.23	959.65	939.76
1.5	0	2.88	-2.88	659.77	635.72
3	1	0.26	-0.26	125	92
4.5	2	1.77	-1.77	412.4	380.82
5.2	2	2.21	-2.21	527.95	495.58
5.7	3	2.39	-2.39	602.63	569.16
6	3	2.35	-2.35	541.44	519.07
7	3	1.9	-1.9	431.88	417.71
7.6	2	1.17	-1.17	289.62	284.96
8	1	0.3	-0.3	90	

Do the same analysis by following the same procedure for the remaining tunnel models that are mentioned earlier and get the results. These results can be analyzed by using graphical representation of the results.

VII. COMPARISON OF PARAMETERS

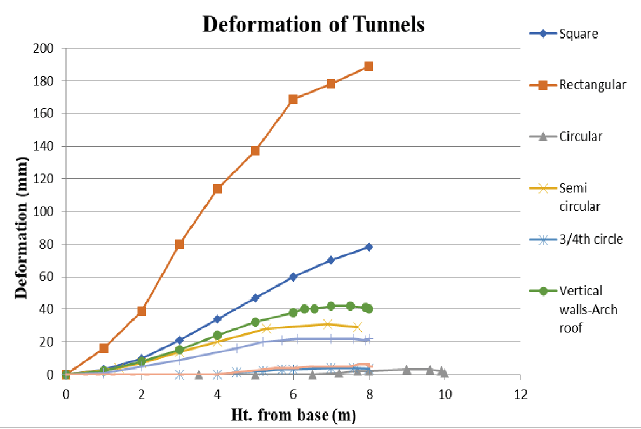

Figure 11. Representation of tunnel deformations

Figure 11 represents the deformation of tunnels analyzed. Observe the max deformation of each tunnel shape. Rectangular tunnel has the maximum deformation among all the tunnels. The smallest value of maximum deformation of tunnel can be observed in circular tunnel. The max deformation of circular tunnel is 0.3mm which is the smallest among all the maximum deformations of tunnels. By this means, it is clear that, for same combination of soil and earthquake loads for the tunnel shapes circular tunnel has shown least deformation among all the tunnel shapes.

CVR Journal of Science and Technology, Volume 21, December 2021
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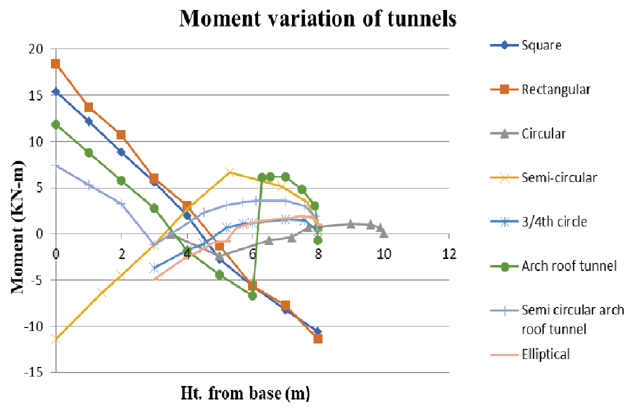

Figure 12. Representation of tunnel moment variation

Figure 12 is drawn to compare the moment distribution of tunnels analyzed. Compare all the moment value of each tunnel model. Rectangular tunnel is having the max moment value at 0m means base. And the moment is positive, so it undergoes sagging up to 4m height. After that –ve moments, means hogging occurs. After rectangular tunnel, semi-circular has the 2nd maximum moment of -11.37KN-m at its base.

Observe the moment graph of circular tunnel. Its values are very nearer to the X-axis. The maximum moment value is -2.43KN-m at 5m height from base. So, it is clear that as the circular shaped tunnel having the least value of maximum moment among the maximum moment values of all the tunnels that are analyzed. Finally, it can be concluded that for same combination loads of soil and earthquake loads for the tunnel shapes circular tunnel has shown least max moment on the structure among all the tunnel shapes.

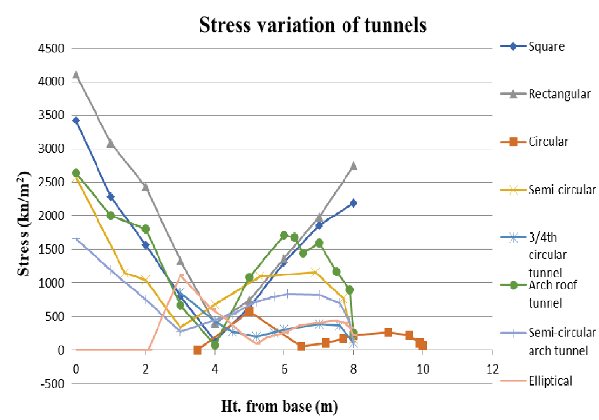

Figure 13. Representation of tunnel stresses

Figure 13 is drawn to compare the stress distribution of the tunnels analyzed. Compare all the stress values of each tunnel model. Rectangular tunnels have more stresses from left half which transfers to the right half which acts as compressive stresses. Among all the tunnels analyzed, it is clear that stress curve of circular tunnel is near to X-axis. And also, the maximum stress value of the circular tunnel is the least among all the max stress values of the other tunnel models. So, it is clear that circular tunnel is strong to resist the shear coming onto it.

VIII. Conclusions

1) Shape is the very important factor to be considered while constructing a tunnel.
2) The circular tunnel exhibits minimum deformations, moments and stresses. Hence, it can be considered as the most efficient shape among the models considered.
3) Soil type also shows an effect on propagation of seismic loads on the tunnel structure.
4) The main advantage is that only linear static analysis is sufficient.
5) Existence of tunnel amplifies the seismic waves on the soil surface and the maximum amplification occurs on the interface of the tunnel and soil.
6) To reduce the deformations, stresses, and moments on the structure, use sand around structure.
7) Sand absorbs seismic waves better than any other soil material.
8) Use high grade concrete, which reduces the deformation of tunnel.

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