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Seismic Analysis and Design of Pune Metro Tunnel

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Abstract - *Pune metro network is one of the major national projects in India. It aimed at developing an elevated and underground transportation system to solve the severe traffic problems in Pune. The underground line includes 5 underground stations which are Shivajinagar, Civil court, Budhwar Peth, Mandai, Swargate and tunnels. The tunnel for Pune Metro Line 2 has a circular cross section of 5.8m internal diameter that consists of a precast segmental lining thickness of 0.275m. This report presents a parametric study on the effects of seismic waves on the tunnel structure through numerical modelling employing the finite – element analysis. Full dynamic analyses were performed employing earthquake motion of maximum magnitude earthquake in Maharashtra which is Koyna earthquake in 1967 of 6.5 magnitude. The analysis of soil-structure interaction was done using the commercial software Rocscience-RS2. The results proved that the 275 mm thick circular cross section can safely sustain the expected static, dynamic and seismic stresses. This research work focuses on the behavior of Segmental lining used for the Pune metro tunnel under seismic loading. Detailed behavior of Pune metro tunnel, designing of Metro tunnel along with seismic loading and its behavior have been studied. Finite element modelling by using software RS2 has been done for 6 cases.*

Key Words: *Tunnel design, seismic analysis, Pune Metro Tunnel, ROCSCINCE-RS2.*

1. INTRODUCTION

Loads induced by seismicity are different in structures resting on ground and structures within the ground surface. Structures resting on ground are mainly affected by inertial forces in relation to body masses, while in underground structures, very low inertial forces are experienced due to very large grade of constraints. Seismic loads are caused due to relative propagation of seismic waves in medium surrounding the tunnel structure. The loads induced by seismic waves in longitudinal direction of the tunnel are not critical as the radial joints may absorb the vibrations to some extent and seismic waves hitting the tunnel cross section may cause ovaling and may lead to failure of the lining.

Damage to the underground structures have been a serious cause during the earthquake and have led to sever damage in recent events of earthquake. e.g., 1995 Kobe (Japan), 1999 Chi-Chi (Taiwan) and 2004 Niigata (Japan) earthquakes where several tunnels and underground structures have suffered severe damages[1]. Therefore, it is essential for the tunnel designer to consider the seismic load effects besides the static load effects. In this research, the effects of seismic loads and action on Pune Metro tunnel is studied on two different cross sections one with maximum overburden i.e. civil court station and one with minimum overburden Shivaji Nagar station and a third case of Koyna nagar is considered as it is the most earthquake prone area in Maharashtra state and Koyna Nagar earthquake acceleration data of 1967 is used which is the maximum magnitude of earthquake till today in Maharashtra State The tunnel were studied employing the finite element program Rocscience-RS2®

Pune metro is mass rapid transport system, which is under construction in Pune, Maharashtra, India. The metro network has a total 54.5km stretch which will be operational in 2022. The 16.59km line 1 is elevated between PCMC Bhawan and Range hill. From range hill it will run underground. Line 2 will be from Vanaz to Ramwadi covering a distance of 14.66 km on an elevated viaduct. These two lines with combined length of 31.25 km are constructed by Maharashtra Metro Rail Corporation Limited which is a joint venture of central and state government.

All the three lines are aligned at the civil court interchange station. Near Agriculture college metro changes its route from elevated to underground.

Number of Reach: -

Reach 1 - PCMC- Range hill

Reach 2 - Vanaz - PMC

Reach 3 - Civil court – Ramvadi

Reach 4 - Shivajinagar -Swargate

Finite element modelling by using software RS2 has been done for 6 cases by considering the real time geological, geotechnical & structural properties. The acceleration triggered by koynanagar earthquake in (1967) which is the maximum magnitude earthquake in Maharashtra till date.

i. Shivaji Nagar Station ODE & MDE (as per IS codes)
ii. Civil Court Station ODE & MDE (as per IS codes)
iii. Koyna Nagar Station ODE & MDE (as per IS codes)
iv. Shivaji Nagar Station with Koyna Acceleration Data.
v. Civil Court Station with Koyna Acceleration Data.
vi. Koyna Nagar Station with Koyna Acceleration Data.

1.1 OBJECTIVES OF THE RESEARCH

The main objectives of the research are:

1. Seismic analysis and design of the Pune metro tunnel using numerical modelling.
2. Seismic analysis and design of the Pune metro tunnel by considering worst earthquake in Maharashtra.
3. Seismic analysis and design of the typical tunnel in most earthquake prone area of Maharashtra.
4. Comparison of: -
   i. Pune metro tunnel – Shivaji Nagar c/s (Least overburden)
   ii. Pune metro tunnel – Civil Court c/s (Max overburden)
   iii. Koyna Tunnel – (Typical tunnel)

2. LITERATURE REVIEW

The effect of seismic loads on underground tunnels have been extensively studied by several researchers in the past. The following literature review presents summary of research papers presented in popular journals on topics similar to current field of study.

M. A. Adam; A. M. Elleboudy; and M. F. Soliman[1] studied the effects of seismic waves on the Cairo metro tunnel located in Egypt. Dynamic analyses employing three different earthquake motions as well as effect of train-induced dynamic load was performed on cairo metro tunnel. The soil-structure interaction analysis was done using the commercial software PLAXIS®. The results stated that the 0.40 m thick segmental lining can safely sustain the expected static, dynamic and seismic stresses. Jia-le Huang; Miao Yu; and Ruan Bin[2] Analysis of seismic response of shield tunnel structure is carried out by dynamic time-history method which is one of the methods with high accuracy. This paper has derived the analytical solution of circular tunnel in no slip. PROSHAKE and ABAQUS are used to calculate the internal force and displacement of Suai shield tunnel structure under the action of artificial wave and Iwate wave. The paper concludes that the analytical and numerical solution after comparison is identical with error less than 10%. Working Group No. 2, International Tunnelling Association[3] The Working Group 2 (Research) of the International Tunnelling Association prepared the guidelines and presented in three parts: Part 1 describes the outline of the procedure of design. Part 2 presents the detailed design methods. Part 3 provides references, including examples of design[3]. The paper presents the basic concepts for design of shield tunnel lining to provide guidelines in designing the lining. Youssef M.A. Hashasha, Jeffrey J. Hooka, Birger Schmidtb, John I-Chiang Yao[4] A summary of the current state of seismic analysis and design for underground structures is represented in the paper. This report describes various approaches used to measure the seismic effect on an underground structure. Deterministic and probabilistic seismic hazard analysis approaches are also briefed. The formation of appropriate ground motion parameters, including peak accelerations and velocities, target response spectra, and ground motion time histories,is stated[4]. For underground structures the seismic design loads are characterized by using deformations and strains imposed on the structure by the surrounding ground, mainly due to their interaction. Seismic designs used for underground structures are also included in the appendix. Rock mass classification-RS2 Tutorial[5]When very less details of soil structure is known at the initial stage of the project rock mass classification scheme is used. One or more rock mass classification schemes can be used to understand the composition and characteristics of a rock mass to provide initial estimates of support requirements and estimates of the properties of the rock mass. In this paper summaries of important classification systems are presented, and an attempt has been made to present all of the pertinent data from the original texts

3. DESIGN PRINCIPLE

Design principle to examine the safety of lining for a shield tunnel for its purpose of usage. The calculation processes including the prerequisite of design, the assumption and the conception of design, and the design lifetime should be expressed in the report in which the tunnel lining is examined in terms of its safety.[6]

4. NUMERICAL MODELLING

4.1 FINITE ELEMENT MODEL

The numerical analysis is carried out using the computer programs: RS2 (Rocscience). The adopted design methodology mainly follows plane-strain transversal model in a vertical section of the tunnel. In a plane strain model the excavations are of infinite length in the out of plane direction, thus the strain in the out of plane direction is zero.

4.2ASSUMPTIONS

1. The material is assumed to be elasto-plastic.
2. The geometry of the tunnel is the same along the tunnel length, permitting the three-dimensional problem to be modelled in two dimensions as a plane-strain analysis.
3. The rock mass surrounding the tunnel is homogenous, isotropic in all directions.
4. In FEM analysis rock mass is subjected to Mohr-Coulomb yield criterion and all the input shear strength parameters have been evaluated accordingly.
5. Parameters and soil behavior: The model represent the geologic layers which are modelled as Mohr- Coulomb strength criterion.

4.3 BOUNDARY CONDITIONS:

1. The upper boundary is kept free to simulate the tunnel under gravity loading.
2. The geometrical dimensions of the model will be chosen in order to minimize the boundary conditions influence on the analysis results in the proximities of the excavated sections.

4.4 STRUCTURAL ELEMENTS:

The primary tunnel lining is modelled as elastic beam elements in 2D plane strain.

4.5 GROUND WATER:

- As per section 7- ODS, 5.02 Cut & cover structures clause 12.9.1 states that –
- Ground water level can be assumed in design for various stages or conditions shall be as follows.
- Construction: - G.W.L at measured max elevation plus 1.5m.

4.6 DESIGN OF SECONDARY LINING

- A reinforced concrete liner is designed as per IS 456:2000 and the design life of tunnel is assured by appropriate construction method, maintenance and quality check.
- It is a common practice to design the tunnel lining element as short column. (Appendix G "FHWA Technical Manual for design of Road tunnels) It is mentioned that tunnel element is designed as a compression member subjected to axial and bending forces.
- Double layer of reinforcement will be necessary as seeing the moment diagram pattern. The moment is alternatively shifting to both sides of lining.
- Due to nature of axial force generated in the final concrete lining (Fig 7.4.1.-1), it is designed as short column. Reinforcement detailing for secondary lining has been done as per IS 456:2000.

4.7 KOYNA ACCELERATION DATA-

The peak acceleration for the ground motion recorded at Koyna in 1967 earthquake are Longitudinal component - 0.63 g, transverse component – 0.49 g, vertical component – 0.34 g, magnitude of earthquake – 6.5, Hypo central distance – 25 km.

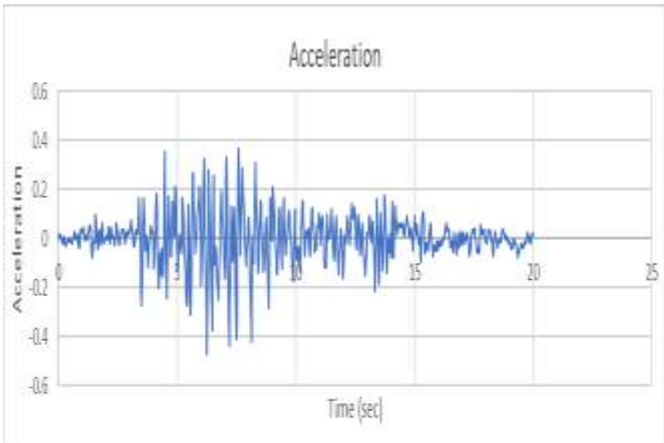

Table -1: Soil properties

	Unit wt. of overburden (MN/m^3)	Youngs modulus (Mpa)	Poissons Ratio	Peak Tensile strength (Mpa)	Peak Cohesion (Mpa)	Friction angle (Degree)
Koyna Nagar						
	30	40000	0.2	11	23	50
Civil Court Station						
Made ground	16-18	1.5-3.5	0.3	-	0	25
HW	25	6250	0.3	2	0.09	30
MW	25	10000	0.3	4	0.25	47
SW	25	12500	0.3	5	1.42	60
Shivaji Nagar Station						
Made ground	16	5	0.3	-	0	25
Sandy clay	18	11	0.3	-	0	25
HW	25	4500	0.3	0.001	0.06	30
MW	25	7500	0.3	0.01	0.16	47
SW	25	14000	0.3	0.3	1	60

5.0 OBSERVATIONS & RESULTS

Table -2: FEM Results for models designed using IS code

	Shivaji Nagar station		Civil court station		Koyna nagar	
	ODE	**MDE**	**ODE**	**MDE**	**ODE**	**MDE**
Axial force (KN)	800	850	630	760	140	210
Bending moment (KNm)	5.59	5.69	5.88	6.23	0.745	0.822
Shear Force (KN)	5	5.11	4.85	5.01	1.88	1.73
Displacement (mm)	3.75	3.81	4.65	4.89	0.677	0.74

Table -3: FEM Results for models designed using Koyna nagar acceleration data

	Shivaji Nagar station	Civil court station	Koyna nagar
Axial force (KN)	930	890	250
Bending moment (KN-m)	5.96	6.7	0.911
Shear Force (KN)	5.22	5.17	1.61
Displacement (mm)	4.02	5.27	0.829

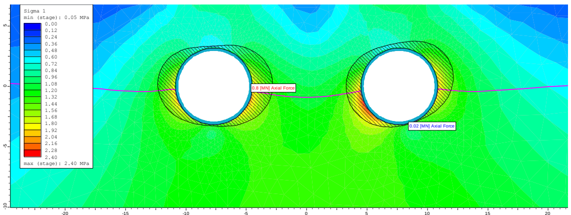

Fig.5.1 Axial force diagram (ODE Shivajinagar station)

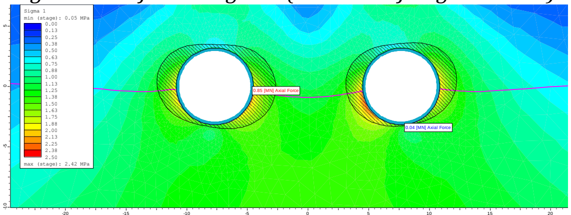

Fig.5.2 Axial force diagram (MDE Shivajinagar station)

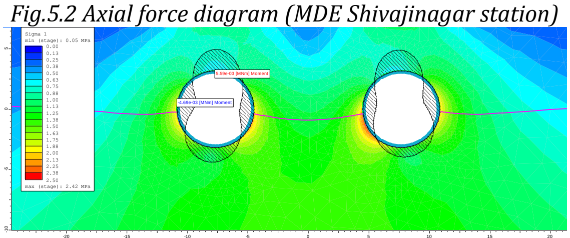

Fig.5.3 BMD (ODE Shivajinagar station)

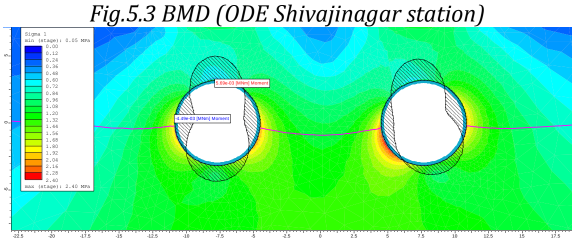

Fig.5.4 BMD (MDE Shivajinagar station)

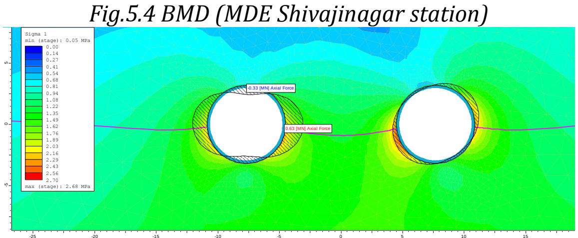

Fig.5.5 Axial force diagram (ODE Civil court station)

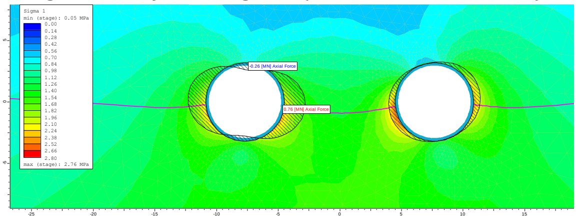

Fig.5.6 Axial force diagram (MDE Civil court station)

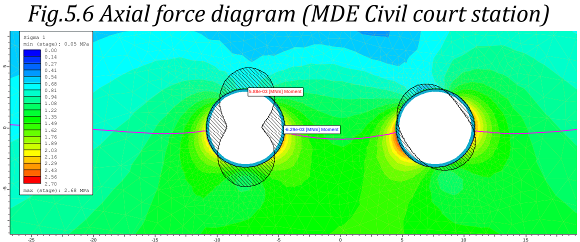

Fig.5.7 BMD (ODE Civil court station)

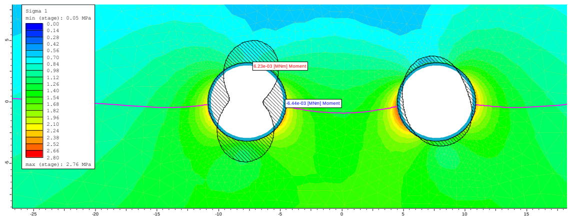

Fig.5.8 BMD (ODE Civil court station)

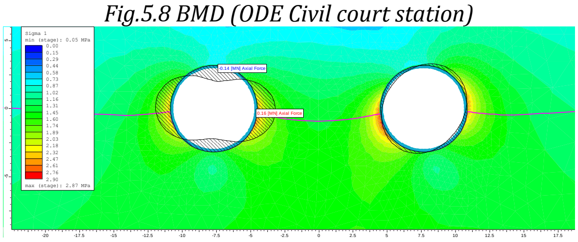

Fig.5.9 Axial force diagram (ODE Koyna nagar)

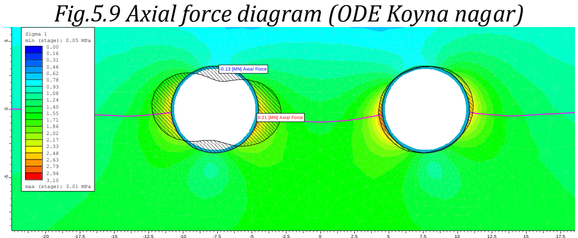

Fig.5.10 Axial force diagram (MDE Koyna nagar)

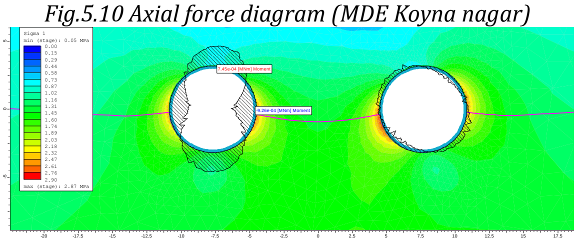

Fig.5.11 BMD (ODE Koyna nagar)

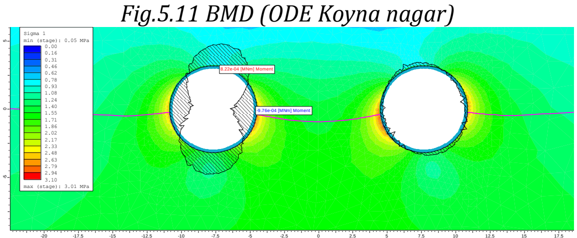

Fig.5.12 BMD (ODE Koyna nagar)

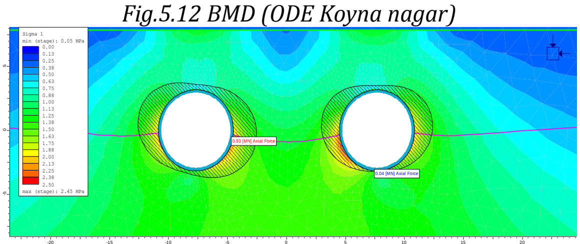

*Fig.5.13 Axial force diagram
(Koyna Acceleration data-Shivajinagar station)*

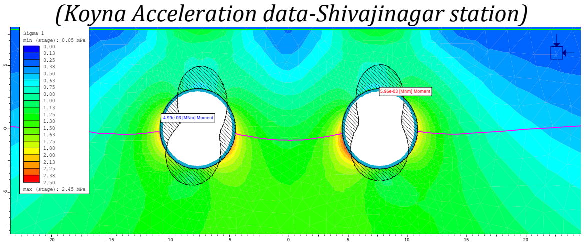

*Fig.5.14 BMD
(Koyna Acceleration data- Shivajinagar station)*

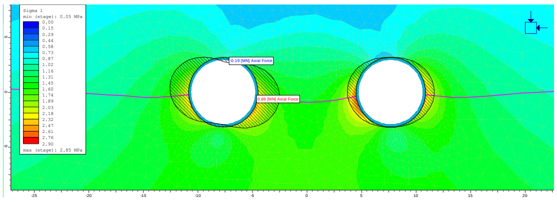

Fig.5.15 Axial force diagram
(Koyna Acceleration Data-Civil court station)

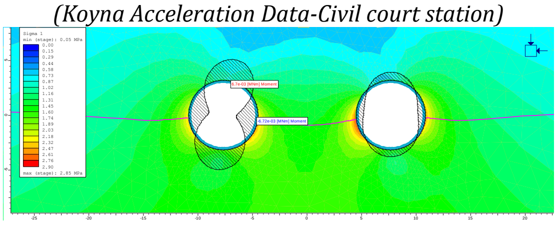

Fig.5.16 BMD
(Koyna Acceleration Data-Civil court station)

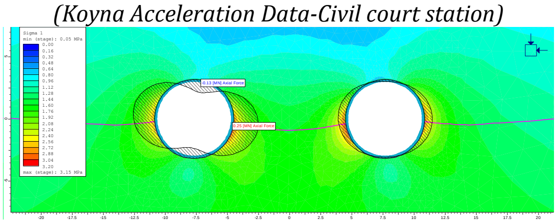

Fig.5.17 Axial force diagram
(Koyna Acceleration Data-Koyna Nagar)

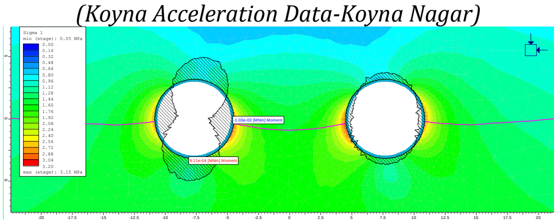

Fig.5.18 BMD
(Koyna Acceleration Data-Koyna Nagar)

6.0 INTERACTION CURVES

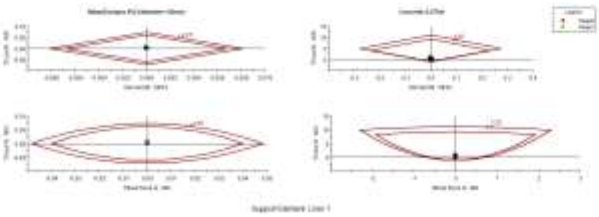

Fig.6.1 Interaction curve (as per IS code- Shivajinagar station)

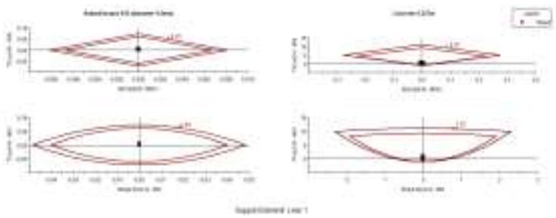

Fig.6.2 Interaction curve (with Koyna acceleration data- Shivajinagar station)

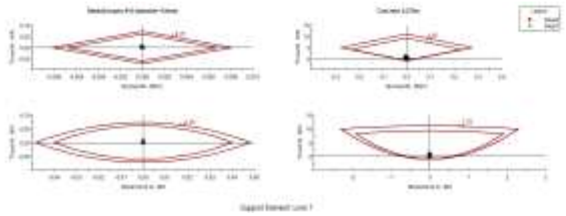

Fig.6.3 Interaction curve (as per IS code- Civil Court station)

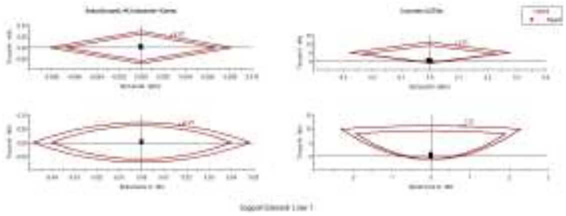

Fig.6.4 Interaction curve (with Koyna acceleration data- Civil Court station)

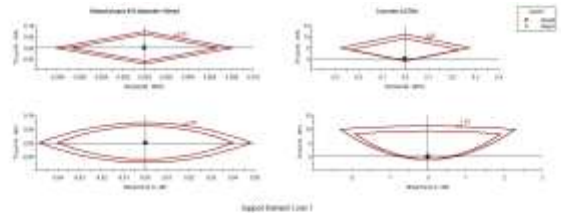

Fig.6.5 Interaction curve (as per IS code- Koyna Nagar)

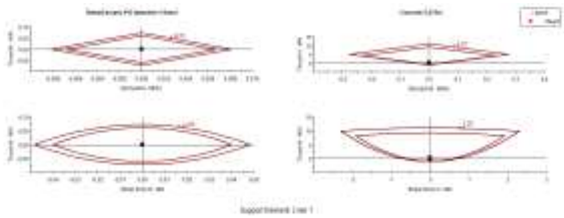

Fig.6.6 Interaction curve (with Koyna acceleration data- Koyna Nagar)

7.0 CONCLUSIONS

- Pune metro tunnel lining of cross section 275mm thickness can safely sustain the seismic force expected due to earthquake at Shivaji Nagar station and Civil Court station.
- Pune metro tunnel lining of cross section 275mm thickness can safely sustain max magnitude earthquake force of koyna nagar (1967).
- Pune metro tunnel lining of cross section 275mm thickness can safely sustain the seismic forces expected due to earthquake in geological strata of Koyna nagar.
- The Displacement in tunnel structures is directly proportional to the bending moment, depth of tunnel.
- The Displacement in tunnel structures is inversely proportional to rock quality index Q.

- There is 112.41% increase in bending moment at Civil Court station compared to Shivaji Nagar station as depth of Civil Court Station is more.
- There is 0.135% decrease in bending moment at Civil Court station compared to Koyna Nagar as the rock quality index of Koyna Nagar is comparatively better.
- Numerical modelling considering seismic forces can produce more realistic results for tunnel design.

8.0 REFERENCES

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