Study of Tuned Mass Damper effect on a structure with fixed and flexible base

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Abstract : To reduce displacement of structure during earthquake Tuned Mass Dampers are used but during design & analysis of Tuned Mass Damper Soil Structure Interaction is not considered. After soil structure interaction is taken into account the results vary compare to fixed base structure. If Soil Structure Interaction is considered during design of Tuned Mass Dampers the overall efficiency is going to increase.

Index Terms - **Displacement, Equivalent Static Loads(ESLs), Fixed base, Flexible base, Inter-storey Drift, Soil Structure Interaction(SSI), Time History Analysis, Time Period, Tuned Mass Dampers(TMD).**

INTRODUCTION

When engineers encounter with soft & weak soil during construction, pile foundation is considered. While designing a pile foundation, with structural loads seismic loads also has to be considered to increase efficiency & durability of structure. During earthquake big structures like bridges, huge oil tank, power plants & dam's foundation failure occurs. Hence these type of big structure are constructed on pile foundation also soil structure interaction to be studied for earthquake loads. The structures while analysing and designing are considered to have fixed or hinged base supported by foundation. So it is assumed that structural deformations are independent of soil rigidity or flexibility. But structure deformation is dependent on soil & foundation properties. Therefore, the structure modelled with soil & pile varies comparatively to a structure modelled with fixed base. Soil is not modelled during design structure because it is difficult to analyse and design, so designers consider only structure with fixed base.

Soil Structure Interaction usually structures element are in direct contact with ground. During earthquake structure response is affected by ground motion and ground motion is affected by structure is known as Soil Structure Interaction. In usual practice as mentioned earlier during analysis of structure which subjected to earthquake soil structure is not considered. Its effect is less on small structures of foundation on hard soil however in case of big structure resting on weak & loose soil, SSI should be considered.

Pile foundation are deep foundation i.e. depth is greater than width of foundation. Pile is used when low bearing capacity soil is there in such type of soil structure is incapable of taking structural loads. These type of foundation subjected to compression load, uplift due super structural loads and lateral loads from earthquake & wind load.

Types of deep foundation are:
1. Pile foundation
2. Pier foundation
3. Well foundation

Pile foundation is a type of deep foundation formed by long, slender members fabricated by RCC or steel, sometimes timber is also used as piles in minor construction works. In case pile foundation depth of piles is at least 3 times more than its breadth.

Pile foundations are generally ideal for massive structures and in the cases where the foundation soil at shallow depth is not fit for resisting excessive settlement and uplift. Pile foundation are mainly used to transfer superstructure loads through weak soil to strong, compact, less compressible rock or stiff soil at depth. Pier foundation consists of massive columns to support the super structure and to transfer superstructure load to hard strata. These columns spread up to some feet above the ground, this foundation is also known as post foundation. Foundation of massive structures such as flyover resting on sandy soil pier foundation is preferred.Well foundations open at both top and bottom, water tight structures fabricated with materials such as RCC, steel or wood.

VIBRATION CONTROL METHODES

Vibration is a mechanical oscillation at an equilibrium. There are periodic & non periodic oscillation. It's an important aspect to control vibration in space craft's, machineries, ships, plans. In civil and infrastructure field vibration reducing methods improved with modernization. RC towers, Multi-storey frames and road bridges are flexible structures therefor they are vulnerable to oscillation when subjected to earthquake and wind. Tectonic action leads to movement of earth which is known as earthquake. Earthquake loads cannot be predicted easily so structure subjected to earthquake should be carefully designed. RC structures are brittle if they subject to high magnitude earthquake it will fail. If structure designed are flexible it will affect users comfort. Reduction of dynamic forces like wind & earthquake is essential topic of civil-engineering. Some amount of earthquake and wind energy is dissipated by over-stressing, inelastic deformation and friction. Structure damping is five percent of overall damping. For energy dissipation artificial damping devices are used in structures.

They are

1. Active control method
2. Passive control method
3. Semi active control method
4. Hybrid control method

To decide which type of vibration control method to use following aspect should be considered like cost of installation, operating cost, efficiency, weight, compactness, safety, maintenance. To minimise structure movement from earthquake many methods were developed recently. Tuned Mass Damper(TMD) is weight connected to structure with dashpot & spring system. These devices are used to reduce dynamic behaviour & as vibration control devices. In tall structures TMD concept is adopted to minimize vibrations. TMD is secondary mass system with stiffness. When building start vibrating it induces frequency to TMD so it vibrates opposite to movement of building leads to decrease in building vibration. TMD as secondary mass system's mass ranges around 0.2%-2.0% of building frame. Now a day's earthquake contains large frequency so more number of TMDs are used.

Tuned Mass dampers is tuned damping device situated at top storey of building and connected by mass. Depending upon natural frequency of frame of building TMD also generate frequency which leads to minimize motion of building. So Tuned mass damper is directly proportional to mass of structure and its frequency. Tuned Mass Damper is designed based on natural frequency of building so it can be move in opposite to structure motion when structure subjected to earthquake or wind loads.

Scope and objective of study

The objective of this project is to study the 15 storey building with & without TMD of fixed base & flexible base during earthquake.

- 15 storey building is considered with different mass ratio for time history analysis of Bhuj earthquake data & Equivalent Static Load analysis.
- Same structure is studied for fixed base and flexible base
- Flexible base is modelled by considering soft soil and pile foundation is considered.
- For analysis SAP 2000 is used

The structure with TMD in fixed base efficiency is checked with flexible base. In practical structure are not fixed as considered in software so by considering soil & foundation real structural response can be seen.

METHODOLOGY

A RC frame structure is to be considered for earthquake analysis for fixed and flexible base with TMD. So far many considered TMD for only fixed base structures but practically the structure doesn't have fixed base.

TMD PRINCIPLE

When there is an earthquake seismic lateral loads will induce in structure, which excite Tuned mass damper to structural fundamental-frequency. TMD will move opposite to structure and the motion of structure due to inertial force will be minimized by the action of TMD.

In software analysis, structure subjects to earthquake, wind, waves (dynamic forces) can be induced easily by software. In small structure viscous and frictional dampers can be fixed on top story to a secure barrier as shown in below

Determination of TMD

To determine TMD for any structure there are some formulas given by different journal's and books

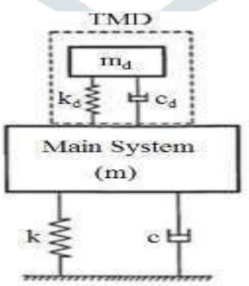


Fig.1 showing the degree of freedom of structure with TMD

Above figure has main structure with mass m, stiffness k And TMD of mass m_d, stiffness of TMD k_d, coefficient of damping c_d.

1. $\omega_d = \sqrt{\frac{k_d}{m_d}}$

where ω_d = TMD's natural frequency , k_d=Damper stiffness, m_d=Damper mass

2. $\xi_d = \frac{c_d}{2 m_d \omega_d}$

where ξ_d =TMD's damping ratio, c_d=damping coefficient

3. $\omega=\sqrt{\frac{k}{m}}$

where ω =Structure's natural frequency, k =Structure's stiffness, m =Structures weight

4. $\xi=\frac{c}{2m\omega}$

where ξ =Damping ratio

5. $\mu=\frac{m_d}{m}$

where μ =Mass ratio

6. $\gamma=\frac{\omega_d}{\omega}$

where γ =Frequency (tuning)ratio

7. $f_d=\frac{f_n}{1+\mu}$

where f_d =Damper's optimum natural frequency, f_n=Natural frequency

8. $\zeta opt=\sqrt{\frac{3\mu}{8(1+\mu)^3}}$

where ζopt =damper's optimum damping ratio

Flexible base & Pile foundation Structural behaviour changes for fixed base to flexible base. In flexible base Soil Structure Interaction is considered. For flexible base foundation must be designed so in this example pile foundation is taken into account because of soil type.

DESIGN FORMULAE FOR PILE & PILE GROUP

DATA REQUIRED

i. Super structures axial load (P) in KN
ii. Soil's unconfined compressive strength (q_u)
iii. m or α (Adhesion coefficient)
   - m=0.4 (pile depth <20 dia)
   - m=0.4 to 1.0 (for deeper piles)
iv. Factor of safety (2.5 to 3)

DESIGN PROCEDURE

➢ Find ultimate bearing capacity of the pile by the following formula: $Q_{up}=(m*C*A_s)+(9*C_s*A_p)$
Where,
C or C_p (Avg. undrained cohesion of soil @ tip of pile) $=\frac{qu}{2}$
A_s=C/S of pile along its length in m^2
A_p=C/S of pile in m^2

➢ Find allow load on pile $Q_u=\frac{Qup}{\text{factor of safety}}$

➢ Find required No. of piles $N=\frac{\text{TOTAL LOAD}}{Qu}$

➢ Find bearing capacity of pile groups
$Q_{UG}=m*C*A_s + 9*C_s*A_p$

➢ Calculate capacity of pile groups $Q_{UGS}=\frac{Qug}{\text{factor of safety}}$

➢ Check for individual pile action $Q_{UGS}= N*Q_{UGS}$

PILE CAP DESIGN BY BENDING THEORY

Pile cap function is to distribute superstructure load equally to every single pile in a group. Pile cap design is done by Bending Theory as per BS 8110 part 1

➢ Find Max. Bending moment (Mu)

➢ Find required effective depth for Max. Bending moment

$d_{req}=\sqrt{\frac{Mu}{0.138 \times fck \times b}}$

➢ Check for one-way two-way shear for calculated depth

ANALYSIS OF STRUCTURE

After many experiments done by researchers on behaviour of structure under influence of earthquake loads leads to design of earthquake resistance structure. From experimental results IS code is formulated i.e. IS 1893. And due to research and experiment IS code is being revised in 1962,1966,1970,1975,1984,2002,2016.

Structure can be analysed by following 3 methods

- Analytical method
- Experimental method
- Numerical method

Analytical method is suitable for small and simple structures. The results obtained from this method is close to solution and very quick. Experimental method consists of scale down model of structure which is to be analysed and equipment's. This method is time taking because to build model and set equipment's also costly. Numerical method is used to solve more complicated problems by some sort of assumption. Comparatively numerical method is more effective to analytical and experimental method. In numerical method Finite Element Method is most used method.

METHODS FOR SEISMIC ANALYSIS OF STRUCTURE

From IS 1893:2002 methods used for seismic analysis are as follows

a) Equivalent Static Method or Equivalent lateral force method
b) Response spectrum method
c) Time history analysis

DETAILS OF MODEL

For experimental purpose 15 storey building is considered having fixed base and flexible base with TMD. Flexible base required pile foundation. Structure details and calculated values of TMD & pile foundation is given below.

GEOMETRICAL PARAMETERS

1. Type of building - SMRF (Special Moment Resisting Frame)
2. Type of structure - RCC framed structure
3. Number of floors - 15 storeys
4. Base support - Fixed Base and Flexible base
5. Height of floor - 3m
6. Grade of concrete - M35 (Super-structure) & M25 (Sub-structure)
7. Grade of steel - Fe500
8. Size of column - 450x450
9. Size of beam - 450x450
10. Slab depth - 150
11. Live load on slab - 3KN/m2
12. Floor finish load - 1KN/m2
13. Seismic zone - Zone5
14. Importance factor - 1
15. Type of soil - 3 (Soft soil)
16. Reduction factor - 5
17. Poisons ratio - 0.4
18. Density of soil - 14.17 KN/m3
19. Modulus of elasticity – 22500KN/m3 of soil

TMD DETAILS - A TMD is nothing but a huge weight located at the top floor of the structure. By referring different books and journals the weight of Tuned-Mass damper should be within limit of 0.25% to 0.70% of total structure i.e. about 1% to 2% of basic frame modal weight. And TMD details are given below.

Table 4.1 Details of TMD for 15 storey building

Total weight of structure KN	3485.84
Natural frequency of structure, ω (rad/sec)	3.621299
	3.621299
	5.432514

Mass ratio (μ)	0.2%	0.5%	1.0%	1.5%	2.0%
Mass of damper in kg	710.9022	1777.2555	3554.511	5331.7666	7109.0221
Weight of damper in KN	6.9717	17.4292	34.8584	52.2876	69.7168
Frequency ratio	0.998004	0.995025	0.990099	0.985222	0.980392
Damping ratio	0.027359	0.043193	0.060933	0.074444	0.085749

Frequency of damper					
Mass ratio	0.2%	0.5%	1.0%	1.5%	2.0%
Mode 1	3.614071	3.603283	3.585445	3.567782	3.550293
Mode 2	3.614071	3.603283	3.585445	3.567782	3.550293
Mode 3	5.421671	5.405487	5.378727	5.352231	5.325994
Damper stiffness					
Mode 1	91.06067	226.2946	448.1192	665.5726	878.7512
Mode 2	91.06067	226.2946	448.1192	665.5726	878.7512
Mode 3	204.9291	509.2688	1008.478	1497.85	1977.602
Effective damping					
Mode 1	1.378672	5.425296	15.23125	27.77508	42.44849
Mode 2	1.378672	5.425296	15.23125	27.77508	42.44849
Mode 3	2.068223	8.13879	22.84925	41.66695	63.67936

PILE FOUNDATION DETAILS

a) L/D ratio = 13

b) Pile dimension,
- B = 0.76 m
- D = 0.76 m
- L = 9.9 m

c) Pile cap dimension
- l = 3.8 m
- b = 3.8 m
- d = 0.7 m
- D = 0.75 m

d) No. of piles = 4 (i.e. 2x2 group)

Model analysis Fifteen storey framed structure of single bay with TMD & without TMD having support fixed also with pile foundation in soft soil is modelled in SAP2000 by considering different mass ratio.

Steps involved for modelling is as follows

- For modelling soil, pile & pile cap brick elements are used i.e. (hexahedral elements with 8 nodes)
- Above mentioned nodes has 3- Degree freedom such as Ux, Uy & Uz, (translation in X, Y & Z)
- For super structure frame elements are used.
- Piles, pile cap & soil are assigned as solid properties.
- In modelling pile dimensions are considered and assigned.
- Properties of structural element such as column, beam, slab, pile, pile cap, & soil are defined and assigned in software to respective element.

LOADS TO BE CONSIDER

- Dead load: from IS 875: 1987 (Part 1) unit weight of material is taken and dead loads are calculated for that structural element by considering its dimension. Software calculate self-weight of frame so it is programme calculated.
- Live load: IS 875: 1978 (Part 2) give live load according to usage of room. Live load is 3KN/m2.
- Super dead load: for floor & roof 1KN/m2 is considered.

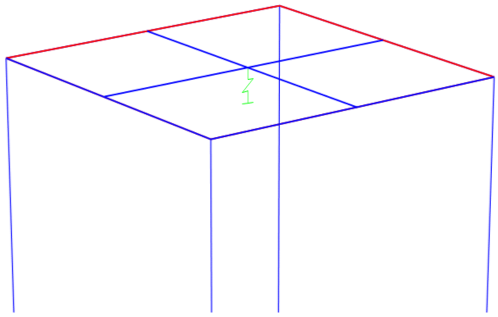
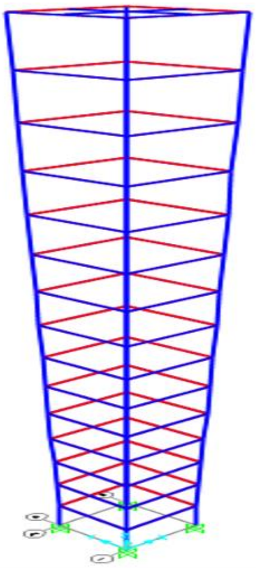
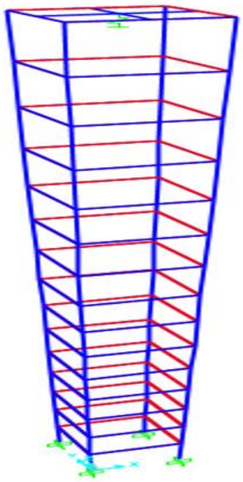


Fig.2 Enlarged view of TMD,





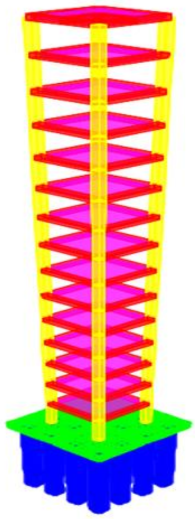


FIG.3 15 storey framed structure, FIG 4 15 storey framed structure with TMD, Fig .5 Extrude view of structure with pile group

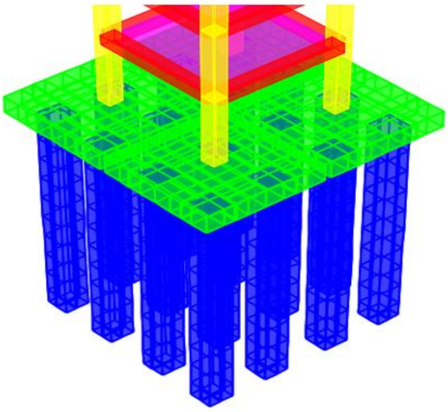


Fig .6 Extrude view of pile group

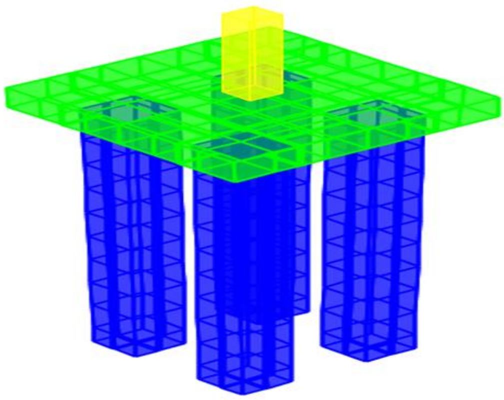


Fig. 7 Extrude view of pile under single column

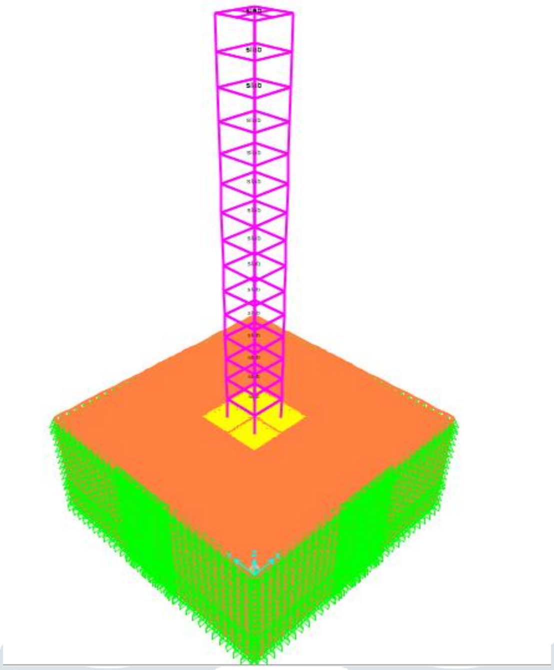


Fig. 8 15 storey structure with soil structure

RESULTS AND DISCUSSIONS

Structure having tuned mass dampers with fixed base and flexible base for Equivalent Static Loads (ESLs) and Time History Analysis for Bhuj earthquake have been analysed for different mass ratio.

Time period variation graphs

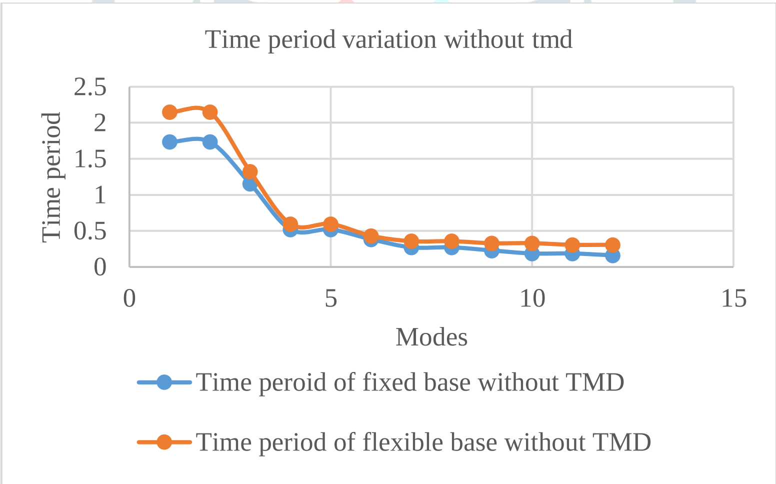


Fig .9 Time period comparison of fixed & flexible base

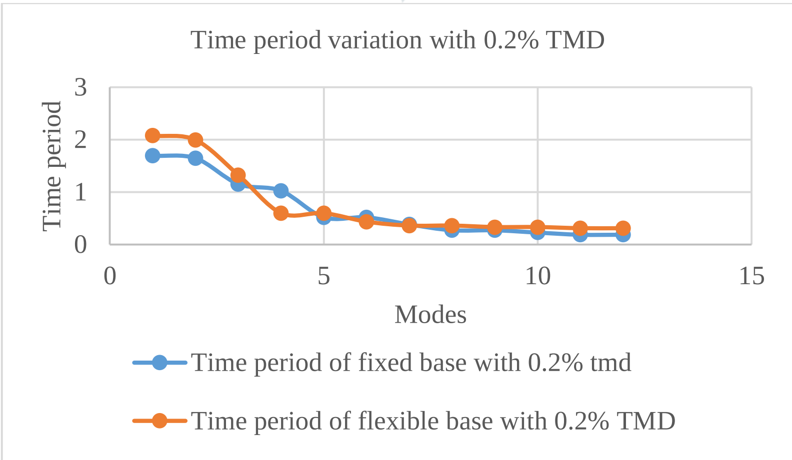


Fig .10 Time period comparison of fixed & flexible base of different mass ratio TMD

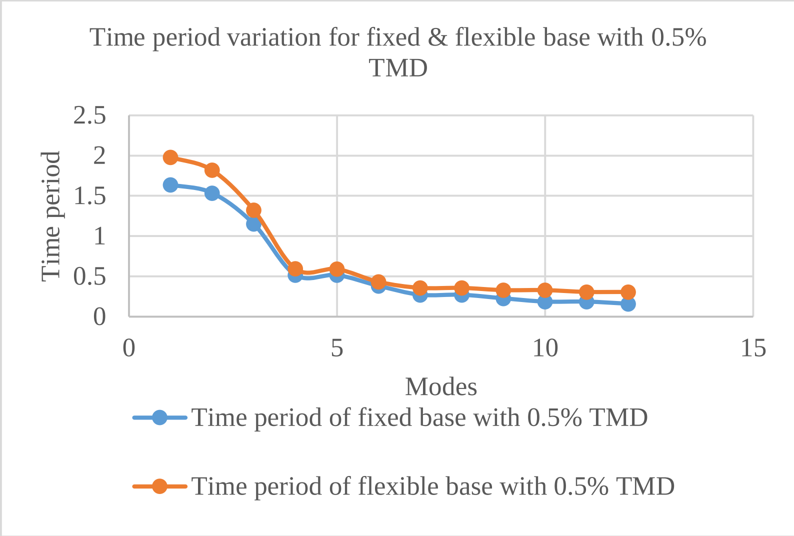


Fig .11 Time period comparison of fixed & flexible base of different mass ratio TMD

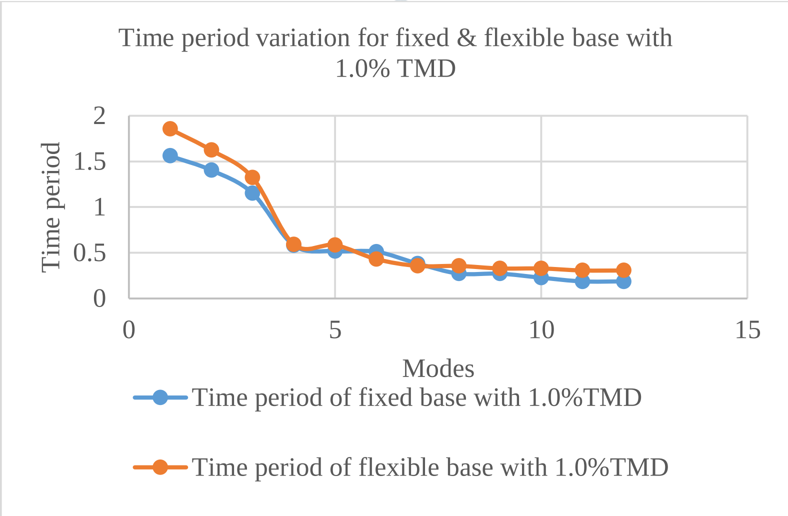


Fig .12 Time period comparison of fixed & flexible base of different mass ratio TMD

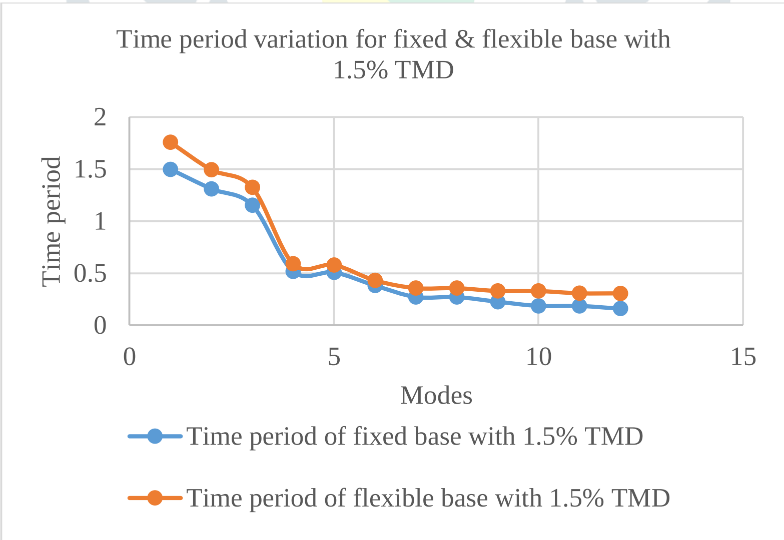


Fig .13 Time period comparison of fixed & flexible base of different mass ratio TMD

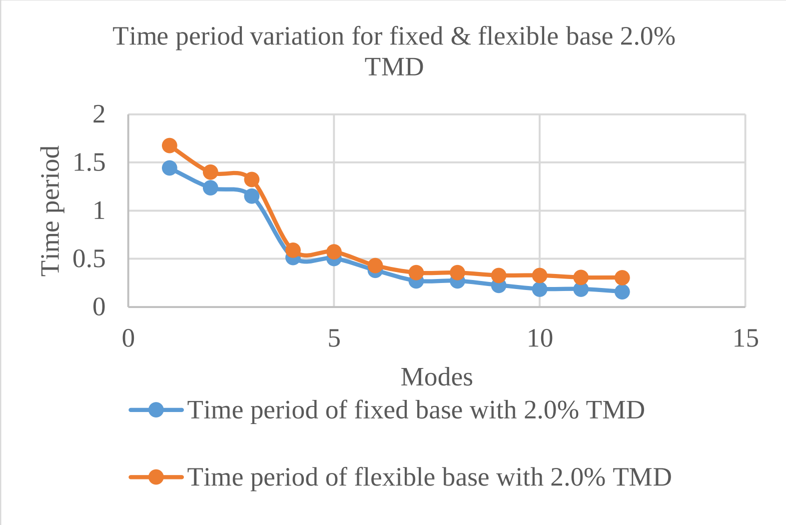


Fig .14 Time period comparison of fixed & flexible base of different mass ratio TMD

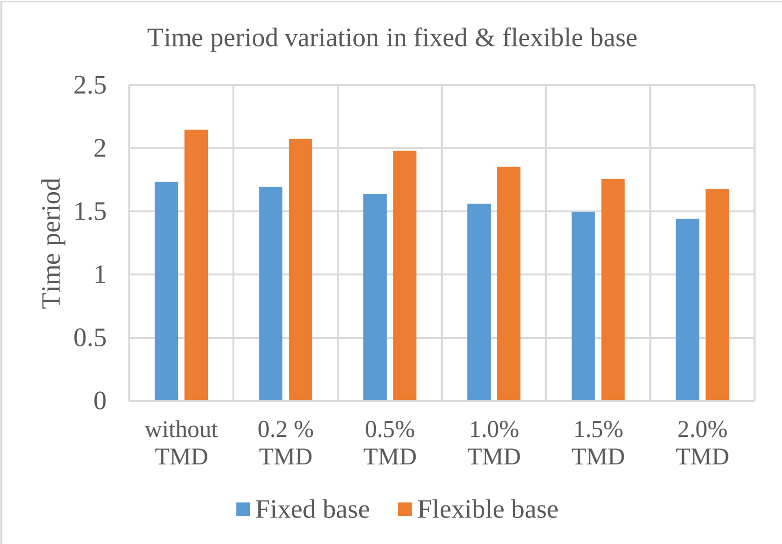


Fig .15 Time period comparison of fixed & flexible base of different mass ratio TMD

From observing graphs, it clearly shows that by increasing mass ratio TMD Time Period of structure increases. Also by comparing fixed base structure with flexible base Time period increases in flexible base.

DISPLACEMENT OF THE STRUCTURE HAVING DIFFERENT MASS RATIO TMD WITH FIXED AND FLEXIBLE BASE

Top storey Displacement due to earthquake loads (mm)				
	Fixed base		Flexible base	
	ESLs	Time History	ESLs	Time History
Without TMD	55.2	91.29	209.1	106.2
0.2% TMD	53.6	86.71	193.7	105.5
0.5% TMD	51.4	79.36	174.8	100.5
1.0% TMD	48.3	68.9	150.8	92.19
1.5% TMD	45.7	63.5	133.1	83.21
2.0 % TMD	43.5	62.88	119.5	73.06

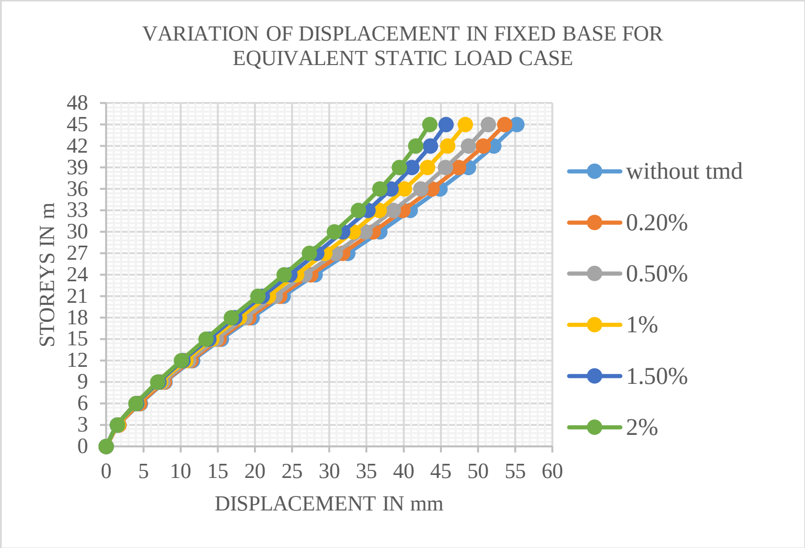


Fig.16 comparison for varying displacement in fixed base with & without TMD of varying mass ratio for ESLs

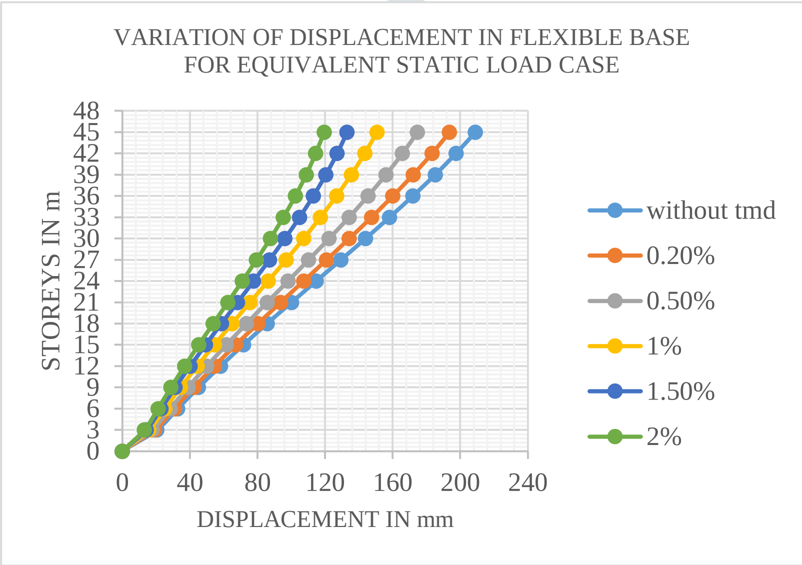


Fig.17 comparison for varying displacement in flexible base with & without TMD of varying mass ratio for ESLs

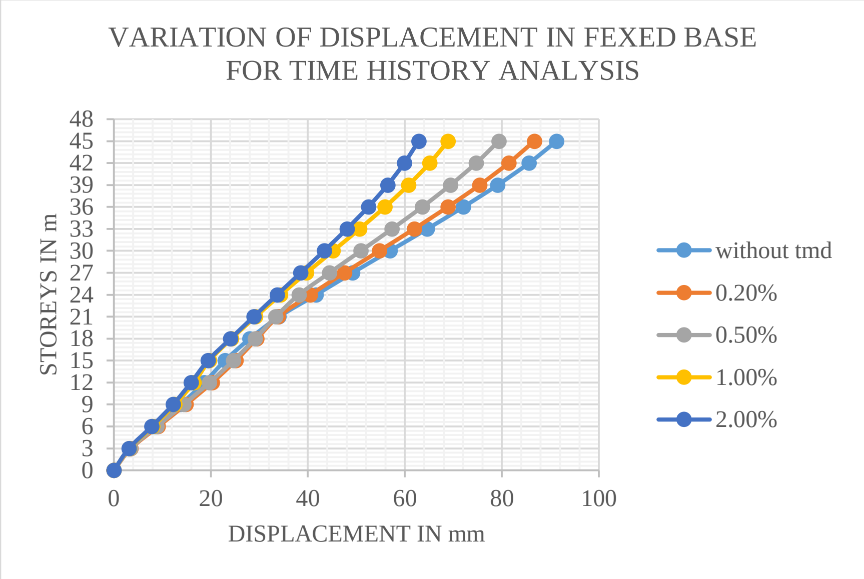


Fig.18 comparison for varying displacement in fixed base with & without TMD of varying mass ratio for Time History Analysis

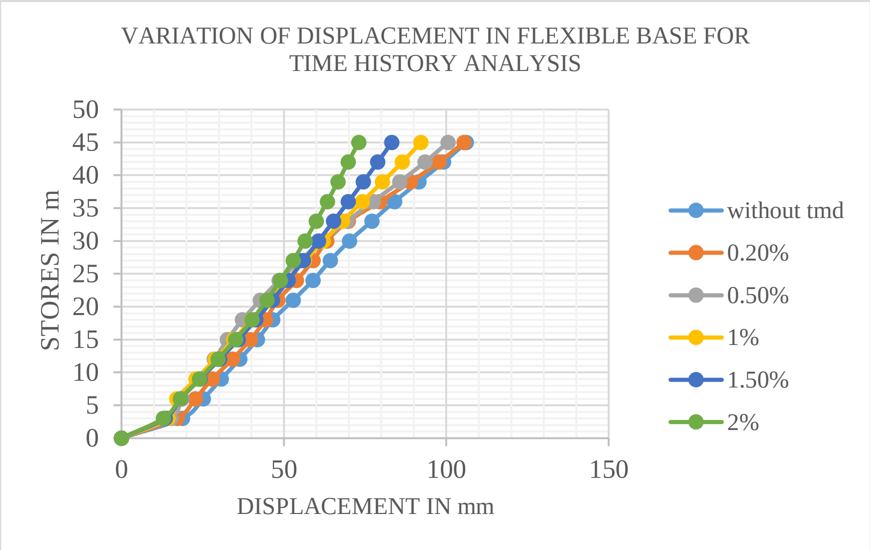


Fig.19 comparison for varying displacement in flexible base with & without TMD of varying mass ratio for Time History Analysis

By comparing all above 4 graphs the displacement is going to decrease as we increase mass ratio so at 2% we will have minimum displacement. Fixed base with TMD analysed, for ESLs decrease in displacement is 21.19% & for Time History Analysis decrease in displacement is 31.12%. Flexible base with TMD analysed, for ESLs decrease in displacement is 42.85% & for Time History Analysis decrease in displacement is 31.2%.

DRIFTS OF THE STRUCTURE HAVING DIFFERENT MASS RATIO TMD WITH FIXED AND FLEXIBLE BASE

Maximum Drift due to earthquake loads				
	Fixed base		Flexible base	
	ESLs	Time History	ESLs	Time History
Without TMD	0.001466667	0.00257	0.00487	0.00233
0.2% TMD	0.001433333	0.0024	0.00453	0.00325
0.5% TMD	0.001366667	0.00216	0.00407	0.00267
1.0% TMD	0.001267	0.00183	0.00357	0.00204
1.5% TMD	0.0012	0.00167	0.00313	0.00154
2.0 % TMD	0.001133	0.00161	0.0028	0.00114

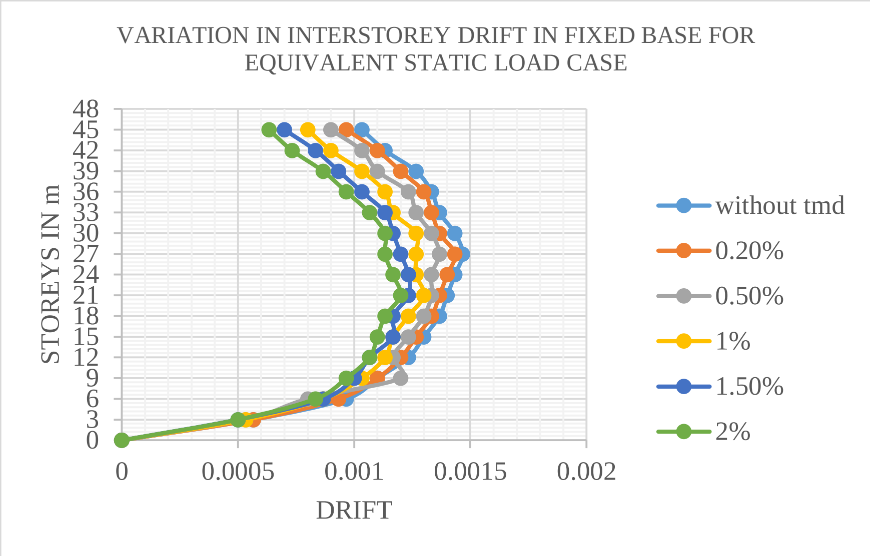


Fig.20 comparison for drifts in fixed base with & without TMD of varying mass ratio for ESLs

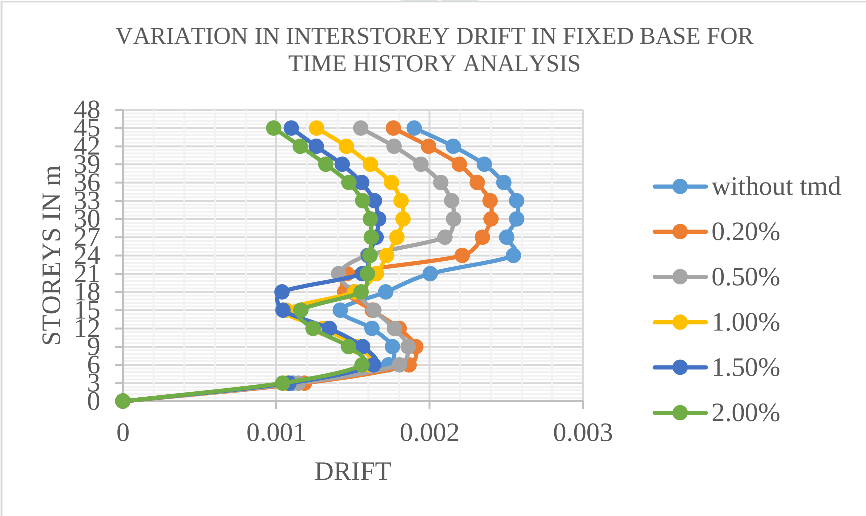


Fig.21 comparison for drifts in fixed base with & without TMD of varying mass ratio for Time History Analysis

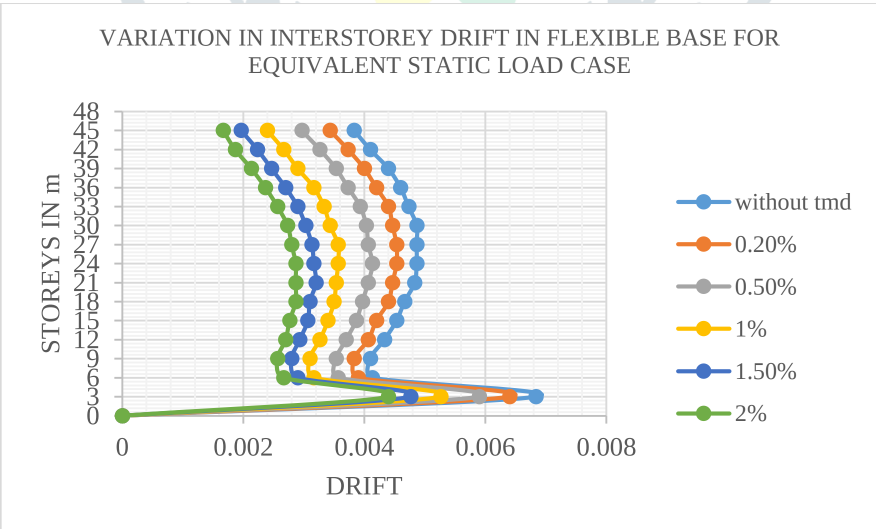


Fig.22 comparison for drifts in flexible base with &without TMD of varying mass ratio for ESLs

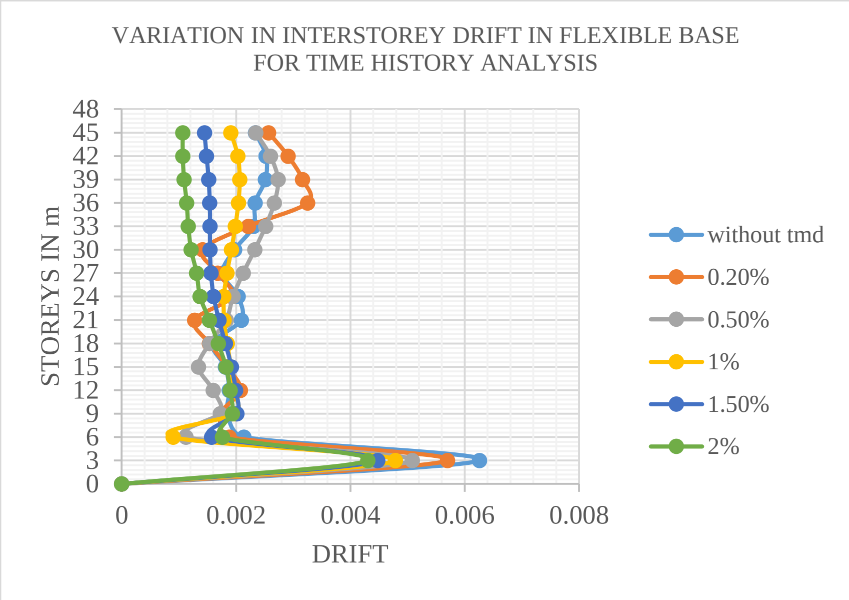


Fig.23 comparison for drifts in flexible base with & without TMD of varying mass ratio for Time History Analysis

As per IS code 1893:2002 clause 7.11 inter-storey drift should be less than 0.004*floor height. By closely observing above graphs its within limit for fixed base & flexible base even after applying TMD drift decreased well within limit. For fixed base it was 0.001467 and decreased to 0.001133 at 2.0% mass ratio TMD. Flexible base its slightly more comparatively & It was 0.00487 and decreased to 0.0028.

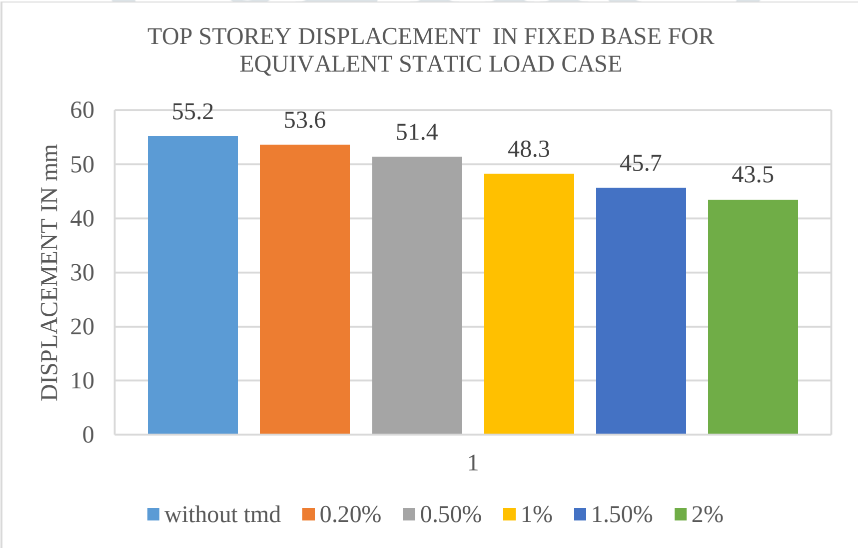


Fig.24 Decrease in top storey displacement in fixed base with & without TMD of varying mass ratio for ESLs

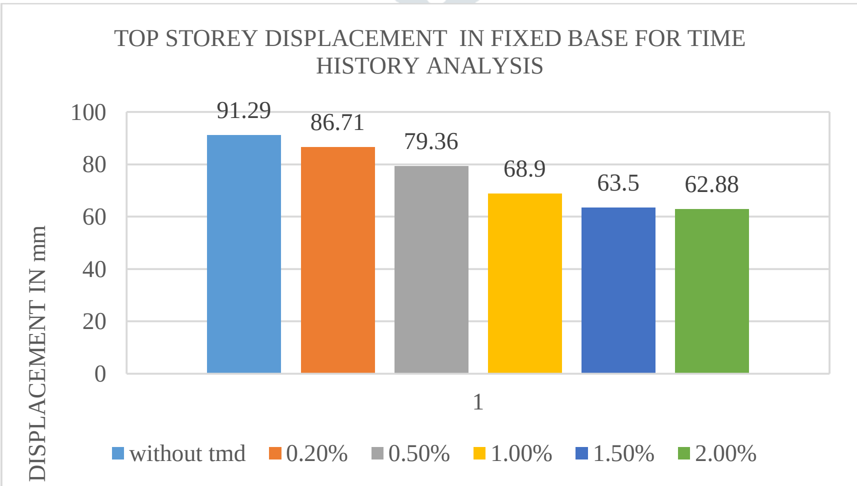


Fig.25 decrease in top storey displacement in fixed base with & without TMD of varying mass ratio for Time History analysis

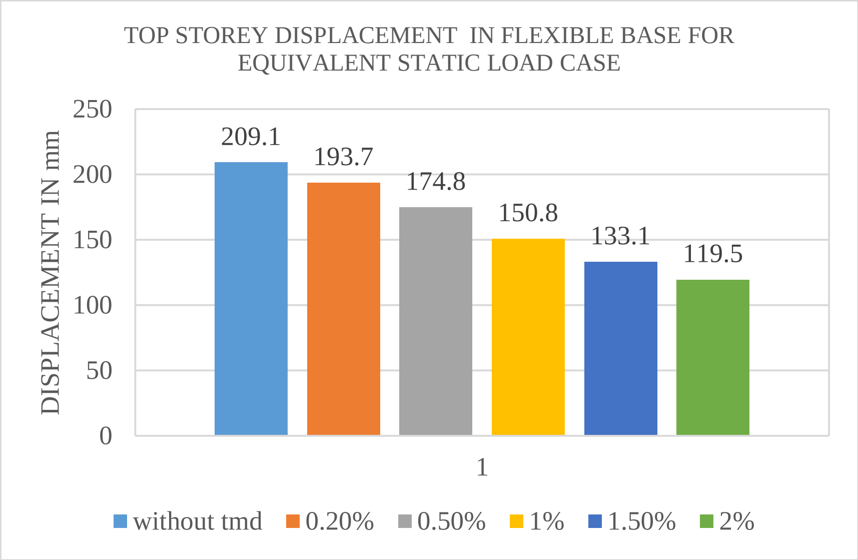


Fig.26 decrease in top storey displacement in flexible base with & without TMD of varying mass ratio for ESLs

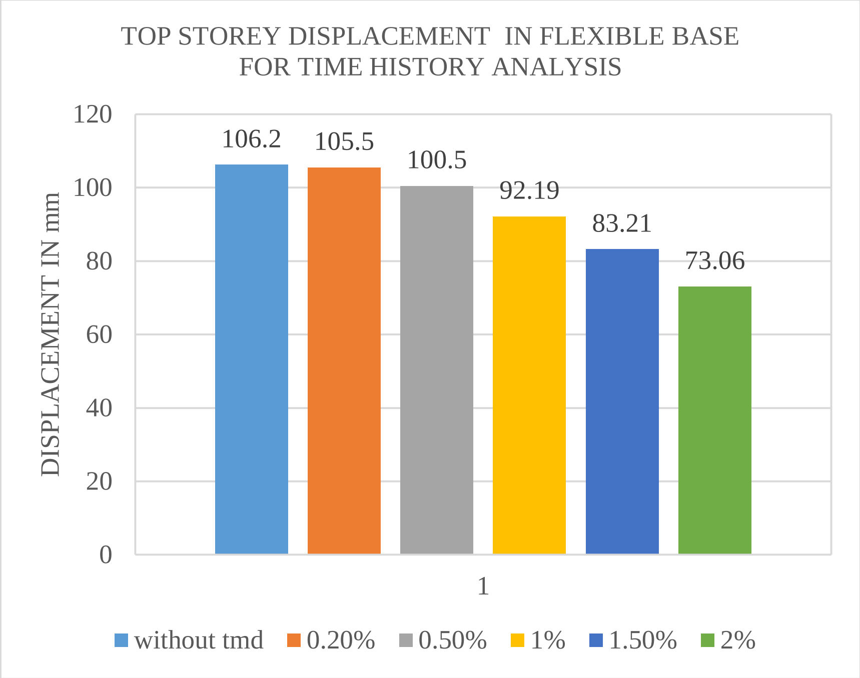


Fig.27 decrease in top storey displacement in flexible base with & without TMD of varying mass ratio for Time History Analysis

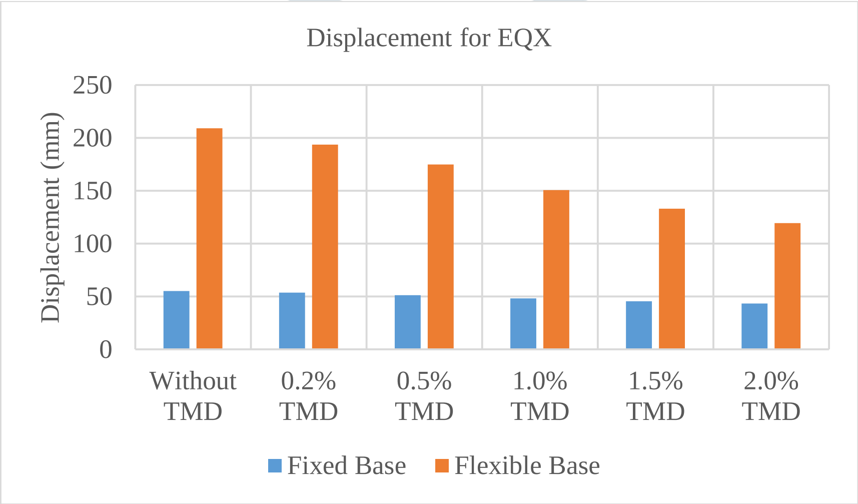


Fig 28 Displacement comparison with fixed base & flexible base for different TMD mass ratio's

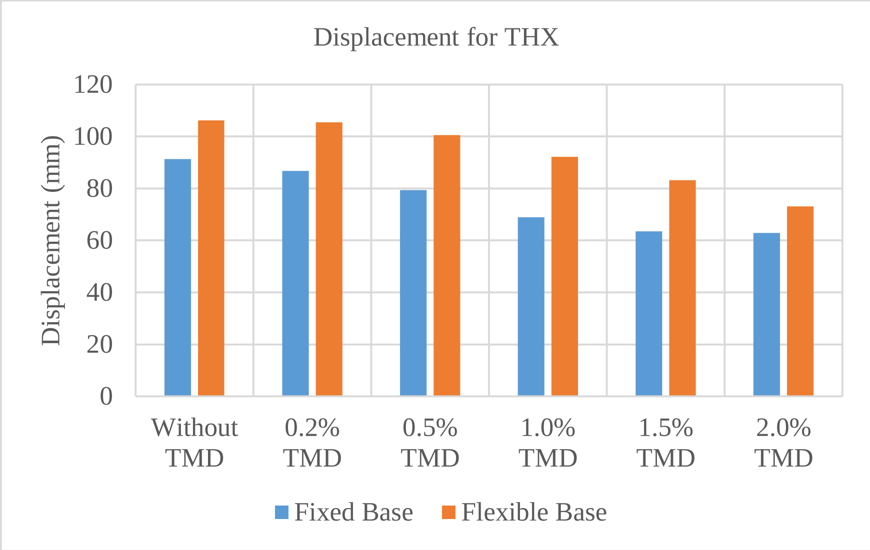


Fig 29 Displacement comparison of Fixed & Flexible base for TMD different mass ratio's

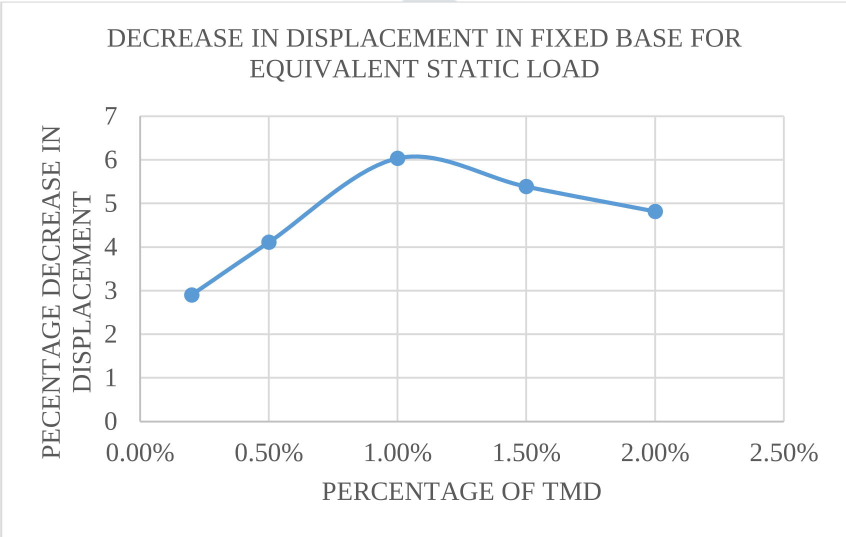


Fig.30 decrease in displacement in fixed base for ESLs

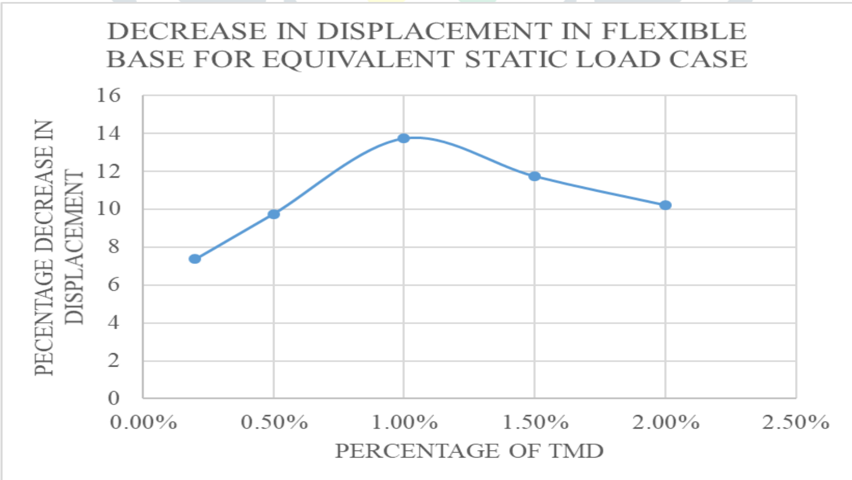


Fig.31 decrease in displacement in flexible base for ESLs

Above graph shows which mass ratio TMD should be more economical to use. By increasing mass ratio displacement may decrease but it will be highly un economical & impractical to use more than 2% mass ratio TMD. By fig.5.3(e) & fig.5.3(f) we can conclude that 1.0% mass ratio TMD is god for even fixed base as well as flexible base.

CONCLUSION:

In present work a 15 storey building with & without soil pile modelled then analysed in SAP 2000 for different mass ratio TMDs. From result obtained following conclusions are made.

- Time period increases as mass ratio of TMD increases.
- At 2% mass ratio of TMD displacement has been decreased to 21.19% at fixed base for equivalent static loads & 42.85% at flexible base for equivalent static loads and 31.12% at fixed base for Time History Analysis & 31.20% at flexible base for Time History Analysis.
- By comparing percentage decrease in displacement for mass ratio 2% is not economical as percentage decrease for mass ratio 1.0%. Which is 24.6% for fixed base and 27.9% for flexible base.
- Inter-storey Drift is within the limit for fixed base structure according to IS1893:2002. Decrease in inter-storey drift for TMD is 18.18% for equivalent static loads, 28.83% in Time History Analysis.
- Inter-storey Drift is more in flexible base model, but after considering TMD inter-storey drift reduces within the limit. Decrease in inter-storey drift is 26.71% for equivalent static loads and 33.9% for Time History Analysis.
- Comparing fixed base with flexible base Displacement & Time period is more in flexible base because of soil structure interaction.

FUTURE SCOPE:

- Further study can be done by considering layered soil & water table effect in soil structure interaction.
- Multiple TMD can be used where inter-storey drift is more.
- By considering different location of TMD.

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