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A Computational Study on Racking Deformation Analysis of Buried Cut and Cover Box Section

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***Abstract*: Racking force is the push which when occurs at the box shaped structural system, it tries to push it out of plumb and the deformation which occurs is called racking. In racking, shear waves travel normal to the axis of structure. The present study has focused on the racking deformation analysis of box type underground sections. Study has been done on cut and cover box section by varying its geometrical parameters like width(W), height(H) and distance from source to site (Ds) that is the distance between focus of earthquake waves and point of interest. The effect of seismic forces occurrence has been also taken into consideration. By varying the components of the section free-field deformation and overall racking deformation has been calculated. In this study "free-field deformation", "soil structure interaction approach" and "simplified frame analysis methods" are followed to get the racking deformation of the structure buried in the ground. These methods have given numerical formulas and design stratagem for racking analysis of buried structural systems. Two type of soil conditions which are stiff soil and soft soil at different magnitude of earthquake has been taken into consideration. Racking deformation calculations has been done manually as well as by the use of MS Excel and comparison has been done in between the racking deformation values.**

***Keywords*: Racking Deformation, Free-Field method, Soil Interaction with Structure, Simplified Frame Analysis method, MS. Excel.**

1. Introduction

Facilities like underground nowadays are the important fragment of our modern civilization. It mainly includes construction of subways, railways, highways, sewage as well as water transport systems in sub-surface. When structure is under the ground the major forces which we consider are the earthquake forces. Hence, the analysis of sub-structure during the occurrence of earthquake is foremost thing that is to be done. The effect of seismic forces on sub-structure are different from super structure or surface structure like buildings, bridges, Dams, Embankments etc. As a sub-structure the different types of section can be constructed like single box section, twin box section, circular section etc. The seismic behavior of box type section is dissimilar from those section which are round or disc-shaped. Box section does not transfer the invariable or steady forces coming over it effectively, as it is done by circular section. Hence to overcome this drawback of box section the thickness of wall, roof slab and base slab is kept more in order to have high stiffness and rigidity.

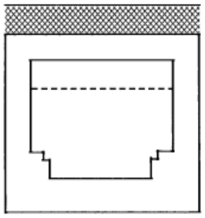
Underground structures are broadly classified into three groups: i) Bored and mined ii) Cut and cover iii) Immersed tube sections. These types of structural systems are mainly used for tunnels of metro, roadways work, transportation of water, transportation of waste like sewage and pedestrian walkways etc.

Bored or mined section are constructed under the ground using the tunnel boring machine (TBM) and are mainly circular in section. In this the soil is not disturbed at the surface and excavated. This is effective method of underground construction in case of overlie structures. *Cut and cover* is that method in which the cutting of soil is done in open, then structure is constructed and again backfilled by soil. This method is only done for shallow structures beneath the ground. The most effective section preferred for this is rectangular/box section because of its ease in construction. It is preferred where the overburden is less than 15m. *Immersed tube* sections are preferred in case of dry dock under the water. They are first constructed, immersed inside the water, sink into position and then placed by using ballasting and anchoring. The geometrical sections of all underground structures for tunnel works are shown in figure 1. Many Scientists have done their studies on the performance of underground structures and gave their points. It is proven that structures which are underground have less damage as compared to the structures which are over surface. With the increase in overburden pressure there is decrease in the damage. Deep sections proved guarded and protected towards shaking of ground due earthquake occurrence then the sections which are shallow. Lined sections are more safe than unlined section. Sections damage can be decreased by the stabilizing the surrounded soil strata and by refining the touch in between the lining and the ground soil strata.

Effects of seismic forces results in ground shaking, ground rupture, landslides, tsunamis, liquefaction and subsidence. Sometimes it causes fire also which consider as secondary effect.

Ground shaking occurs due to passage of earthquake waves through the ground and ranges from small earthquake to devastating large earthquakes.

Ground rupture occurs when earthquake waves travel along a fault actually break the earth's surface.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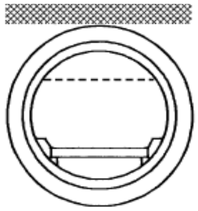
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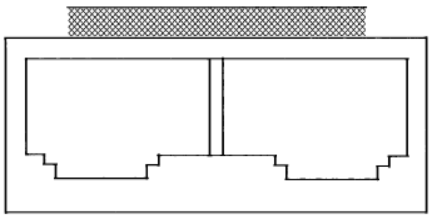
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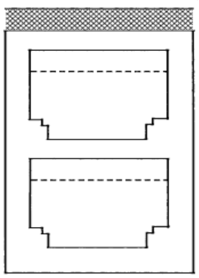
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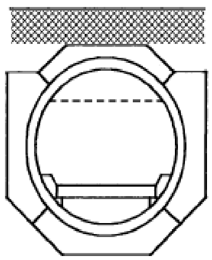
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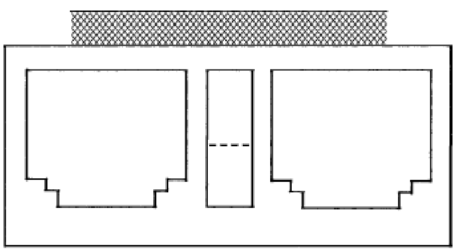
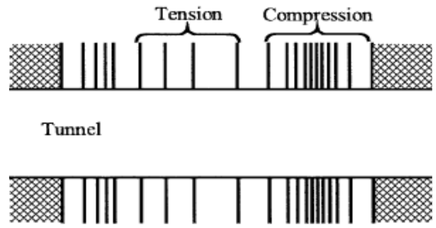
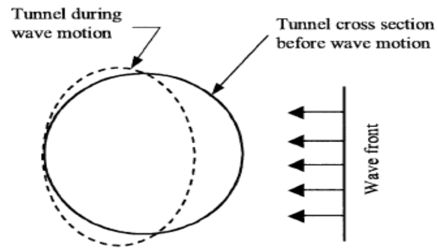

(f)

Fig. 1. Cross Section of Tunnels a) Cut and Cover (Rectangle), b) Bored and Mined, c) Twin Box Cut and Cover (Mid Wall), d) Cut and Cover Section (e), (f) Immersed Sections (Single and Multiple cellular box/tube)

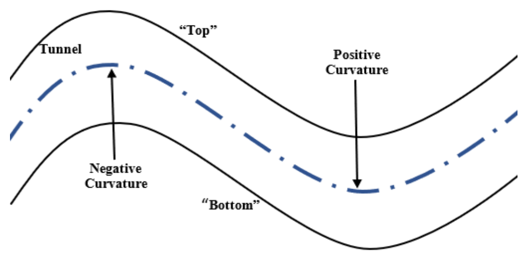
Landslides occurs due to the continuous shaking of ground and by direct rupture. *Tsunamis* also called as tidal waves are the series of water waves which occurs when seafloors move vertical along with the earthquake waves. *Liquefaction* occurs when soil sediment loses their solidity and made to float on ground in groundwater. *Subsidence* occurs when sand blows, sand volcanoes, form when pressurized jets of ground water break through the surface. The other factors which effects underground structures are the shape, structure's depth from ground, dimensioning of the structure and surrounding soil properties etc. The behavior of underground section is considered as beam which is elastic in nature and subjected to distortions by the soil strata around the section. There are different types of structure deformations due to the motion of seismic waves are shown in figure 2.



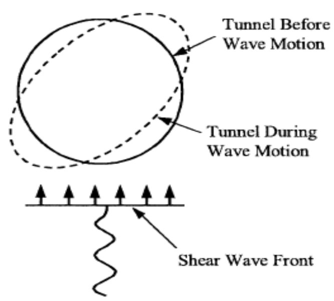
(a) Compression-Extension



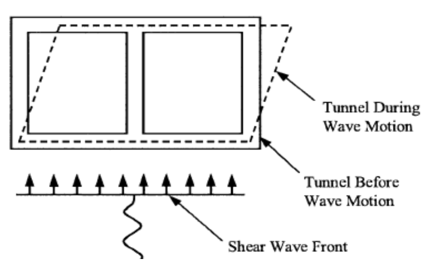
(b) Compression in circular section



(c) Bending along longitudinal axis



(d) Ovalling deformation



(e)Racking deformation

Fig. 2. Effect and Deformation Due to Seismic Waves

Axial compression and extension which occurs due to the component of earthquake wave that produce motion parallel to the axis of the section and results in compression and tension. *Longitudinal bending* occurs due to the particle motion perpendicular to the longitudinal axis. *Ovalling and racking* deformations occurs in the structure when shear wave travels normal to the section axis which results in the distortion in the shape of the structure.

Seismic racking deformation can be done by various design approaches. There are different methods which can be implemented are Dynamic earth pressure approach, Free-field deformation approach, Soil structure interaction finite-element analysis and Simplified frame analysis approach. The present study deals with the racking deformation of structures. The present study focused on racking deformation analysis by combined approach of all methods which are mentioned in the abstract. Free-field deformation describes ground strains caused by earthquake waves in the absence of structure or excavation. These deformations do not take the influence of interaction between the structure and the surrounding soil strata. This method is easy to understand and effective design tool when distortions produced due to seismic waves are small. In soil structure interaction approach the design of cut and cover rectangular/box section requires keen consideration of soil structure interaction because of increased structure stiffness and potential towards the large deformations due to shallow burial. It gives best soil structure system. It gives best results in complicated section with variable soil properties. It is suitable in all conditions. Simplified frame analysis approach provides an easy and adequate design of rectangular structures. It gives good approximation of soil structure interaction. It provides good structural response.

2. Design Procedure

By using the free-field approach, soil structure interaction and simplified analysis method racking deformation analysis of buried structural system is done and various literature papers has been followed which are mentioned in the references. Following design steps are followed and racking deformation is obtained.

a) Select the box section geometrical parameters like member sizes (W, H), Soil properties on basis of geotechnical report and history of earthquake occurred in that area according to present design requirements.
b) Find out the maximum/peak ground acceleration (a_{max}) on the basis of maximum design (MDE) and operating design earthquake (MDE).
   i. *For cut and cover type box sections*
      MDE =0.36g
      ODE=0.18g
   ii. *For bored type sections*
      MDE =0.24g
      ODE =0.12g
c) Selection of seismic zone (Z) as per the seismic activities of the ground according to IS:1893-2002. Table 1 shows the zone factors for different seismic zones.

Table 1
Seismic Zones According to IS:1893-2002

Earthquake Zone(Z)	**II**	**III**	**IV**	**V**
Earthquake Intensity	Low	Moderate	Severe	Very Severe
Zone Factor	0.10	0.16	0.24	0.36

d) Calculate peak ground acceleration(a_s) at a specified depth (D) from the ground level up to the top level of box section.

$$a_s = Depth\ Factor * a_{max}(MDE) \quad (1)$$

Depth factor is selected according to data given in table 2. As the depth of section/tunnel from the ground level increases, there is decrement in the ratio of ground movement at the section depth to the movement at the ground surface.

Table 2
Ratio of Ground Movement at Depth to Movement at Ground Surface

Tunnel Depth (D_T)	**Ratio of Ground Movement at Tunnel Depth to Movement at Ground Surface**
<=6	1.0
6-15	0.9
15-30	0.8
>30	0.7

e) Calculate peak ground velocity (V_s) during the seismic wave propagation in the ground. The value of peak ground velocity (V_s) can be calculated by selecting the magnitude of earthquake (M_w), Source to site distance (D_s), type of soil and ratio of peak ground velocity to peak ground acceleration given in table 3.

$$\frac{V_s}{a_{max}} = Ratio \quad (2)$$

f) Find out apparent velocity (C_m) of seismic wave propagation in soil. It is calculated on the basis of type of soil and number of blows(N) obtained from the standard penetration test. Different empirical and experimental formulas are given by equation 1.3, 1.4 and 1.5 are used according to the type of soil strata.
   i. For silty sand $C_m = 86 * N^{0.42}$ m/sec (3)
   ii. For sand $C_m = 79 * N^{0.434}$ m/sec (4)
   iii. For all soils $C_m = 82.6 * N^{0.43}$ m/sec (5)

In this study the stiff and soft soil are taken into consideration and equation 3 and 5 are used.

According to the data given in table 3 the shear wave velocity for soil sediments are shown in the table 4.

g) Calculation of maximum free-field shear strain of sub-strata (γ_{max}). It is calculated by obtaining the values of peak ground velocity (V_s) and apparent velocity (C_m) of shear wave.

Table 3
Ratio of Peak Ground Velocity to Peak Ground Acceleration in Rock and Soil

Magnitude of Earthquake (M_w)	$\frac{V_s\left(\frac{cm}{sec}\right)}{a_{max}(g)}$ = **Ratio**		
	Source to Site Distance, Ds (Km)		
	0-20	**20-50**	**50-100**
Rock			
6.5	66	76	86
7.5	97	109	97
8.5	127	140	152
Stiff Soil			
6.5	94	102	109
7.5	140	127	155
8.5	180	188	193
Soft Soil			
6.5	140	132	142
7.5	208	165	201
8.5	269	244	251

Table 4
Velocity of Shear Wave on the Basis of Soil Sediment

Type of Sediment	**Velocity of Shear Wave (Km/hour)**
Rock	>=2700
Stiff	720-9720
Soft	<720

$$\gamma_{max} = \frac{V_S}{C_m} \qquad (6)$$

h) Calculation for free-field distortion due to shear waves in sub-strata($\Delta_{Free\text{-}Field}$). It depends upon the height of the section(H).

$$\Delta_{Free-Field} = \gamma_{max} * H_S \qquad (7)$$

i) Calculation of shear modulus of soil/rock medium (G_m). It depends upon the soil density (ρ) and apparent velocity (C_m) of the seismic wave/shear wave.

$$G_m = \rho_m * C_m * C_m \qquad (8)$$

j) Calculation of flexibility ratio (F). Flexibility ratio for rectangular section can be calculated by both computational analysis and manual methods by implementing some formulas which are empirical or experimental on the basis of number of barrels.

i. For more than one-barrel frame

For this simplified approach is computational analysis in order to avoid the complexity of results.

$$F = \frac{G_m * W_S}{f * H_S} \qquad (9)$$

f is the load required to have a unit deflection in the structure.

ii. For Single barrel frame (I_R=I_B)

In this the moment of inertia of roof slab (I_R), invert slab (I_B) and moment of inertia of side walls (I_S) are calculated.

$$F = \frac{G_m}{24}\left[\frac{{H_S}^2 * W_S}{E * I_w} + \frac{H * W_S^2}{E * I_R}\right] \qquad (10)$$

Where
E - Plane strain elastic modulus of frame
W_s-Width of the section(m)
H_s-Height of the section(m)

iii. For Single barrel frame ($I_R \neq I_B$)

$$F = \frac{G_m}{12}\left[\frac{H_S * W_S^2}{E * I_R} * \Psi\right] \qquad (11)$$

$$\Psi = \frac{(1+b)(a+3b)^2 + (a+b)(3b+1)^2}{(1+a+6b)^2} \qquad (12)$$

$$a = \frac{I_R}{I_B} \qquad (13)$$

$$b = \frac{I_R}{I_w} * \frac{H_S}{W_S} \qquad (14)$$

If
F = 0; the structure is rigid and there is no occurrence of racking.
F < 1; the structure is taken as stiff relative to the medium and hence there is decrement in racking occurrence.
F = 1; the structure and soil strata have identical stiffness, so the structure will undergo approximately free-field deformation.
F > 1; the structure racking deformation is amplified relative to the free – field, though not because of dynamic amplification, but because of the cavity-like presence.
F → ∞; the structure does not have stiffness, so it will have deformations similar to the perforated ground.

k) Calculation of racking coefficient(R). Racking coefficient can be calculated by using graph for normalised structure deflections for circular and rectangular sections depending upon the flexibility ratio(F) and poisson's ratio (μ) shown in figure 3 and 4. The solid line shows the values for circular section and triangle shows the values for rectangular section. Present study has opted the empirical formula given by equation 15 to calculate the racking coefficient.

$$R = \frac{4(1-\mu)}{[(3-4*\mu)]/F]+1} \qquad (15)$$

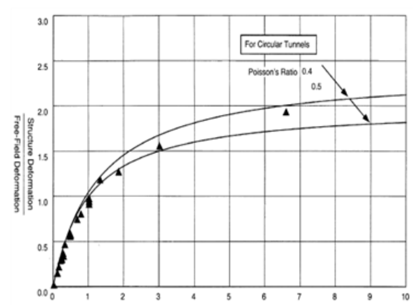


Fig. 3. Normalised Structure Deflections for Circular and Rectangular Sections

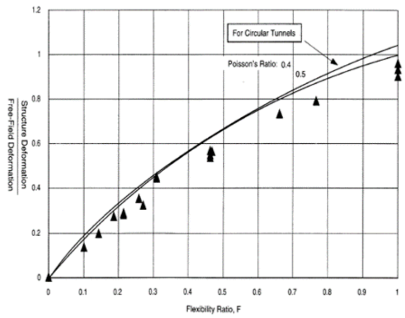


Fig. 4. Normalised Structure Deflections for Circular and Rectangular Sections

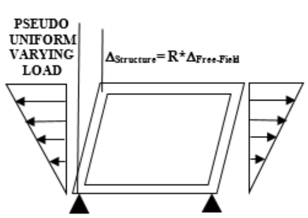
l) Calculation of over-all racking deformation of the structure ($\Delta_{Structure}$).

$$\Delta_{Structure} = R * \Delta_{Free-Field} \quad (16)$$

Equation 16 is the product of racking coefficient (R) and free-field deformation ($\Delta_{Free-Field}$). Figure 5 shows the simplified frame models of box section under the application of concentrated load at the top node/corner of the section(A) and application of uniformly varying load having load intensity zero at the bottom with some varying value of load at the top(B). By both the ways racking deformation is calculated in the structure. Frame analysis of this type is mainly done in software like Staad.Pro.

m) Apply the racking deformation of the structure in simplified frame analysis.

n) Internal forces which are produced in the structural member due to racking, add into the other loading components. If the permanent structure is modelled and designed for at-rest earth pressure condition, then no increase in pressure before or after the earthquake occurrence is not necessary to be taken into consideration in the analysis. If it is designed at active pressure condition, then active earth pressure as well as at-rest are taken into consideration for dynamic loading.



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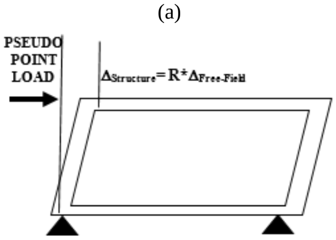

(b)

Fig. 5. Simplified Frame Model for Deep and Shallow Tunnels/Sections

o) If the results formed in step "n" gives adequate structure capacity, then design is satisfactory otherwise revise.

p) If there is increment in flexural strength in step "n", then the rotational ductility is to be checked. In case of in-elastic deformations special provisions are to be taken into consideration. For ODE and MDE the resulting deformation in the structure are kept within the elastic limit range. Redistribution of moments in the structure is done according to ACI 318 and acceptable plastic hinges deformation is taken into consideration for the structure. If the unacceptable plastic hinges pattern occurs then revision of design is to be done again. Maximum design earthquake (MDE) is termed as the maximum level of ground movement due to earthquake felt at the site. Operating design earthquake (ODE) is an earthquake which has probability of occurrence once in a design life of the structure or facility.

q) If the strength criteria and ductility criteria do not match and deformation in the structure is getting exceeded to allowable deformation limits, then structure is redesigned and revised.

r) Apart from the racking deformation the effect of vertical acceleration and longitudinal strain produced due the friction's drag is also taken into consideration.

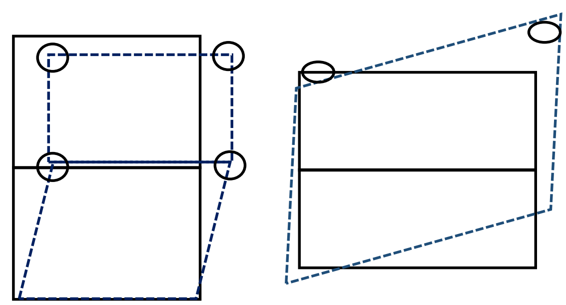

Fig. 6. Formation of Acceptable Plastic Hinges in Single Structural Member for Buried Rectangular Box Section

Figure 6 and 7 shows the formation of acceptable and unacceptable formation of plastic hinges pattern in individual structural element. Formation of two plastic hinges on single member is acceptable but formation of three plastic hinges on single member is unacceptable.

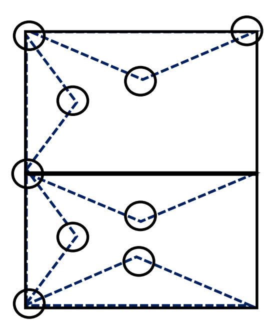

Fig. 7. Formation of Unacceptable Plastic Hinges in Single Structural Member for Buried Rectangular Box Section

The vertical or upward earthquake forces which mainly occurs at the top of cut and cover section can be obtained by having product of peak ground acceleration in vertical direction and soil backfill mass.

3. Geometrical Parameters and Soil Properties

Geometrical parameters of buried structure which are used in this study are shown in table 5 and 6.

Table 6 shows the different cases that the present study has taken into consideration for the racking deformation analysis. Various combination of geometrical parameters given in table 5 are analyzed for two types of soil conditions which are stiff and soft under different magnitude of earthquake with variable site to source distance. Source is considered as the focus of the earthquake waves generation from where seismic waves starts travelling.

Table 5
Section Geometrical Parameters

W_s (m)	H_s (m)	H_{eff} (m)	D (m)	T_{RS} (m)	T_{BS} (m)	T_{SW} (m)
6	4	3.5	5	0.50	0.50	0.50
6	6	5.5	5	0.50	0.50	0.50
6	12	11.5	5	0.50	0.50	0.50
6	16	15.5	5	0.50	0.50	0.50
6	20	19.5	5	0.50	0.50	0.50

Table 6
Different Cases for Racking Deformation Analysis

Soil Type	M_w	D_s (km)			Z	N	ρ_w(kg/m^3)
Stiff	8.5	10	30	60	0.36	24	1720
Soft	7.5	10	30	60	0.36	24	1720

Where
W_s-Width of the section
H_s-Height of the section
H_{eff}-Centre to center height of the section
T_{RS},T_{BS} &T_{SW}-Thickness of roof slab, base slab and side wall
M_w-Magnitude of earthquake
D_s-Source to site distance
Z-Zone factor
N-Number of blows
ρ_w- density of soil

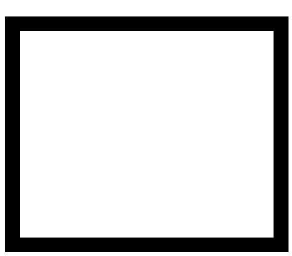

Fig. 8. Box Shaped Section

Figure 8 shows the box section of buried structure which is analyzed for development of racking in it by varying its geometrical, soil properties as well as seismic criteria.

4. Result and discussion

The present study focused on racking analysis of box section buried in the ground. The box section shown in figure 8 has been analyzed by varying its geometrical parameters, soil properties as well as seismic magnitude as given in table 1,2,3 and 4. The sections are analyzed for the racking deformation which occurs when earthquake waves travels normal to the axis of the structure and waves tries to push the structure out of plumb. There are different methods/approaches which are implemented to analyze the racking deformations. This study has taken into consideration the free-field approach, soil structure interaction approach and simplified frame analysis method in order to get the total racking deformation in the structure. The design steps which are followed, explained in section 2(Design procedure). Various empirical as well as derived formulas are explained which are given by the combination of all the approaches from equation 1.1 to 1.16. The geometrical data, soil types and seismic data are given in table 5 and 6. For every case the total racking is calculated and comparison is done. Racking deformation depends upon the width and height of the box section. If height of the section more than width then it is observed that structure experience more deformations. If depth of section from the ground level is less, then also it experiences more deformation. It means that deeper is the structure in the ground more is the safety. Cut and cover method is not suitable for the deep construction of sections/structure in the ground. Hence when structure is buried at the shallow depth in the ground then, it experiences more deformations. Cut and cover method is more suitable and reliable for rectangular type sections and deformation in it is termed as racking and it is also called as horizontal shear deformation. The propagation of seismic waves differs according to the sediments or soil type in which it is travelling and according to that peak ground acceleration, peak ground velocity as well as peak ground displacement also varies. Table 3 shows the ratios of peak ground velocity to the peak ground acceleration with respect to distance of site from source and type of soil. Mainly acceleration and velocity of seismic waves are high in soft soils. Site to source distance also effects the deformation in the structure. Inertial properties of the section like thickness of the vertical as well as horizontal members also effects the deformation of structure. The Following cases from I to VI are taken into consideration for analysis and hence, sections are analyzed for racking deformation and each value is compared with each other in order to check the stability of structure. By observing the calculated values, it can be seen that how the racking deformation values varies according to the variation in the magnitude of earthquake, source to site distance(km), geometrical parameters and type of sediments. In this study the depth of the box section from the ground level is kept constant as a shallow buried structure. With the decrease in the magnitude of the earthquake there is decrement in the deformation of structure. Wider section provides more stability to the structure as compared to the structure having more height.

Case I Mw=8.5, Ds=10km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	11.90	27.81	17.94	41.92
6	4	7.93	18.31	11.96	27.60
6	12	23.80	56.35	35.87	84.94
6	16	31.73	75.39	47.83	113.63
6	20	39.67	94.43	59.79	142.33

Case II Mw=8.5, Ds=30km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	12.43	29.05	16.27	38.02
6	4	8.29	19.12	10.85	25.03
6	12	24.86	58.86	32.54	77.05
6	16	33.14	78.74	43.39	103.07
6	20	41.43	98.62	54.23	129.10

Case III Mw=8.5, Ds=60km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	12.76	29.82	16.74	39.11
6	4	8.51	19.63	11.16	25.75
6	12	25.52	60.42	33.47	79.26
6	16	34.02	80.83	44.63	106.03
6	20	42.53	101.25	55.79	132.81

Case IV Mw=7.5, Ds=10km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	9.26	21.63	13.87	32.41
6	4	6.17	14.24	9.25	21.34
6	12	18.51	43.83	27.74	65.68
6	16	24.68	58.64	36.98	87.87
6	20	30.85	73.44	46.23	110.05

Case V Mw=7.5, Ds=30km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	8.40	19.62	11	25.71
6	4	5.60	12.92	7.33	16.93
6	12	16.79	39.76	22	52.10
6	16	22.39	53.19	29.34	69.70
6	20	27.99	66.62	36.67	87.30

Case VI Mw=7.5, Ds=60km

W_s (m)	H_s (m)	Stiff Soil		Soft Soil	
		Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)	Δ_{F-F} (mm)	$\Delta_{Structure}$ (mm)
6	6	10.25	23.95	13.40	31.32
6	4	6.83	15.77	8.93	20.62
6	12	20.49	48.53	26.80	63.47
6	16	27.33	64.92	35.74	84.91
6	20	34.16	81.31	44.67	106.35

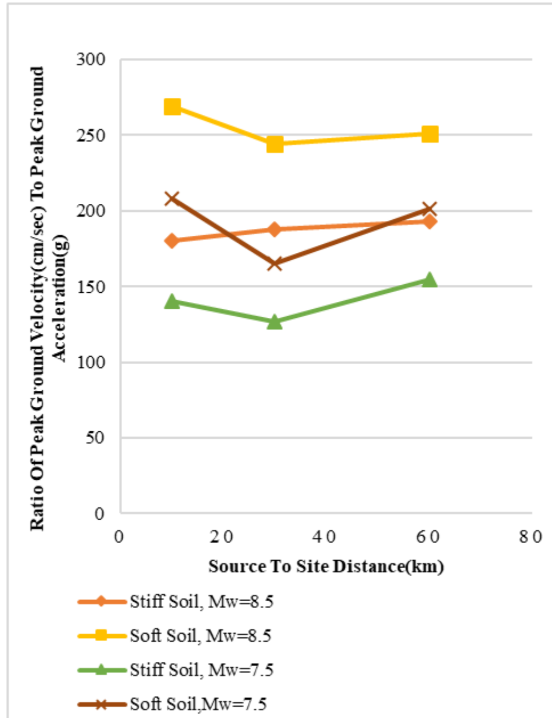

Fig. 9. Variation of Peak Ground Velocity to The Peak Ground Acceleration According to Magnitude of Earthquake and Soil Sediment

Graph in figure 9 shows that how the ratio of peak ground velocity and peak ground acceleration varies with the change in magnitude of earthquake and source to site distance for stiff and soft soil. Peak ground velocity (PGV) is the strong ground motion which occurs during the earthquake shaking. and Peak ground acceleration (PGA) is equal to the amplitude of the largest absolute acceleration recorded on an accelerogram at a site during a particular earthquake.

5. Conclusion

From the results it is observed that sections buried in soft soil are more vulnerable towards racking as compared to stiff soil/sandy soil and also signified about the probability of exceedance in racking deformation by assuming different cases from I to VI. Inertial properties like adequate thickness of horizontal and vertical members should be taken for effective performance. Speed of the earthquake shear waves in soft soil are high. Hence the values of peak ground velocity and acceleration of shear waves or earthquake waves are comparatively more in soft soil than stiff and rocky soils. Structure constructed nearer to source of earthquake waves experiences more destruction. Sections having balanced height to width ratio are more stable. Wider sections with less height gave efficient results and stability. Hence in cut and cover method the sections with more height as compared to width should be avoided as they are more vulnerable towards cracking and racking.

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