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Soil Structure Interaction in Indian Seismic code: Recommendations for Inclusion of Potential Factors

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Abstract: The extent of the damage caused due to earthquake depends greatly on the characteristics of ground motion which indirectly depends on the wave propagation path, source and site characteristics. With the advent of massive construction on poor soils caused due to limitation of land, the response of soil during earthquake has also become prominent. Hence special consideration is given to the Soil-Structure Interaction (SSI) effect while constructing massive as well as tall structures like water tanks, chimneys etc. Indian code, IS 1893: Part 4-2005, specified formulae have clearly shown a general trend of increase in natural period and decrease in base shear of structure due to SSI. This paper mainly deals with finding the adequacy of code defined standards for considering soil structure interaction effects. The results derived from various researches and codes of different countries are compared with the Indian code provisions. Indian code does not take into account the effect of seismic intensity on shear modulus and effect of damping. Also, the quality control in today's construction work increases the significance of effect of embedment in SSI. These effects are considered using the formulae derived in existing literature and consequently the effect on the response of the structure is determined. A parametric study is also carried out on a 150 m tall RCC chimney considering the effect of seismic zone on structural response of chimney by incorporating strain-dependent shear modulus, damping effect and embedment effect. The results obtained show that the embedment and damping factor affect the base shear considerably and hence there is a critical need of inclusion of these factors in Indian code. The paper also shows that, if relevant provisions from some international codes and literatures are suitably amended, a substantial variation in the base shear force can be achieved, hence in many cases ensuing structural work cost saving. Overall with this study, the paper attempts to address the legitimate concern of design engineers regarding the potential variation in design values, especially for soft soil sites.

Keywords: *Seismic soil structure interaction, Indian seismic code, Embedment effect, Damping factor, Effective shear modulus*

1. Introduction

Earthquake force consideration in design has always been given prominence due to its unpredictable nature. The topic has gained attention continuously due to the evolution of new design procedures and also the inclusion of new factors in design. Earlier it was assumed that the soil characteristics have no considerable influence on the behavior of the structure due to ground motion. However, due to certain destructive collapse in the history (e.g. Kobe earthquake, 1995), it was found out that the behaviour of site soils is one of the three major factors that can significantly influence the intensity of ground shaking due to an earthquake at any given site, the other two factors being the earthquake source mechanism and the geology of the seismic-wave path. If a lightweight flexible structure is built on a stiff foundation, an appropriate assumption we make is that the input motion at the base of the structure is the same as the free-field earthquake motion. However, if the structure is very massive, and the soil is relatively soft, the motion of structure at its base may be considerably different than the free-field motion. Soil-structure interaction consideration during design makes a structure more flexible and hence, increasing the natural period of the structure (Chowdhury and Dasgupta, 2008). Furthermore, SSI effect also increases the effective damping ratio of the system. The smooth idealization of design spectrum recommends minor seismic response with the increased natural periods and effective damping ratio due to SSI. This assumption leads to the consent that SSI can be conveniently neglected for conservative design of the structure. This assumption is only valid for certain class of structures and soil conditions, such as light structures in relatively stiff soil. However, the population increase and limitation of land has forced the user to construct a tall and stiff structure without concerning about the type of soil. Moreover, the increase in natural period of the structure due to consideration of SSI is not always advantageous as recommended by the simplified design spectrums. Soft soil sediments can considerably lengthen the period of seismic waves and the increase in natural period of structure may lead to the resonance with the long period ground vibration (Chowdhury and Dasgupta, 2008). Formulae have been specified in Indian seismic code IS 1893- Part 4 for including the effect of the SSI in the design. Indian code mainly

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incorporates the effect of soil by means of stiffness. However, it has been found that stiffness factor should be modified according to damping and effective shear modulus for more realistic results. Also, Quality control has increased now a day in comparison to the past hence the effect of embedment cannot be neglected. Results derived from several codes (IS 1893: Part 4, EN 1998-5:2004) and research papers in terms of formulae (Arya et al., 1984; Richart et al., 1970) have been taken as reference and the above mentioned factor have been incorporated in the calculation of effective horizontal seismic coefficient. The results obtained show the significant influence of these modified parameters on the response of the structure and hence highlight the necessity of inclusion of the factors in the Indian seismic code for a better earthquake resistant and cost effective design.

2. SSI Provisions in Indian Seismic Code

2.1 Time Period of Vibration

As per clause 14 of IS 1893 – Part 4, the time period of vibration of stack like structures when fixed at base shall be determined using the formula

$$T = C_T \sqrt{\frac{Wh}{E_S A g}} \quad (1)$$

Where

C_T= coefficient depending upon the slenderness ratio of the structure given in Table 6 of IS 1893 (Part 4),
W = total weight of the structure including weight of lining and contents above the base,
h = height of structure above the base,
E_S= modulus of elasticity of material of the structural shell,
A = area of cross-section at the base of the structural shell,
g = acceleration due to gravity.

2.2 Horizontal Seismic Force

As per clause 16 of IS 1893- Part 4, the horizontal seismic coefficient using the period T shall be obtained from the spectrum given in IS 1893(Part 1) as

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g} \quad (2)$$

Where

Z = zone factor in accordance with Table 2 of 1S 1893 - Part 1,
I = importance factor as specified in Table 8 of IS 1893-Part 4,
R = response reduction factor as given in Table 9 of IS 1893- Part 4, and
S_a/g = spectral acceleration coefficient for soil sites as specified in fig. 1 of IS 1893 - Part 1.

2.3 Design Shear Force and Moment

As this paper is restricted to the static response calculation of the structure, for these cases, Indian code has specified equivalent static lateral force method for analysis. This simplified method can be used for stack like structure (IS 1893: Part4).

2.3.1 Equivalent Static Lateral Force Method

The design shear force, V and design bending moment, M, for such structures at a distance X from the top, shall be calculated by the following formulae:

$$V = C_v A_h W D_v \quad (3)$$
$$M = A_h W \hat{h} D_m \quad (4)$$

Where

C_v = coefficient of shear force depending on slenderness ratio k specified in Table 6 of IS 1893-Part 4,
A_h, = design horizontal seismic coefficient,
W = total weight of structure including weight of lining and contents above the base,
h = height of center of gravity of structure above base, and
D_v, D_m= distribution factors for shear and moment respectively at a distance X from the top as given in Table 10 of IS 1893 - Part 4.

2.4 Effective Time Period due to SSI Effect

The effective fundamental time period of the structure given by Velestos and Meek, 1974, depends on fixed base time period as well as rocking and horizontal stiffness.

$$T' = T\sqrt{1 + \frac{K\prime}{K_x}\left(1 + \frac{K_x \hat{h}^2}{K_\theta}\right)} \quad (5)$$

Where

T = the fundamental period of the structure for fixed base case,
$\acute{k}$ = the stiffness of the structure when fixed at the base, defined by the following:

$$K' = \frac{4\pi^2 W}{gT^2} \quad (6)$$

$\hat{h}$ = height of centre of gravity of structure above base,
K_x= the horizontal stiffness of the foundation defined as the horizontal force at the level of the foundation necessary to produce a unit deflection at that level, the force and the deflection being measured in the direction in which the structure is analyzed, given by Richart et. al. (1970).

$$K_x = \frac{32(1-\nu)Gr_o}{(7-8\nu)} \quad (7)$$

K_θ = the rocking stiffness of the foundation defined as the moment necessary to produce a unit average rotation of the foundation, the moment and rotation being measured in the direction in which the structure is analyzed, given by Richart et. al. (1970).

$$K_\theta = \frac{8Gr_o^3}{3(1-\nu)} \quad (8)$$

g = the acceleration of gravity in m/s^2,
γ= Unit weight of soil, kN/m^3,
G = shear modulus of soil, $G = \rho V_s^2$
ρ = mass density of soil in kg/m^3,
V_s = shear wave velocity of the medium in m/s,
υ = Poisson's ratio of soil,
r_o = radius of circular raft foundation

3. SSI modified Parameters

The parameters such as effective damping ratio, embedment correction factor and effective shear modulus have been obtained from various literatures and codes and are incorporated in the calculation for finding the effect of their inclusion on the response of the structure.

3.1 Effective Damping Ratio due to SSI effect

The material damping ratio for a soil structure system is given (Kramer 2004)

$$D' = K_e\left(\frac{D}{K'} + \frac{D_x}{K_x} + \frac{D_\theta}{K_\theta}\right) \quad (9)$$

Where,

Ď=Damping ratio of the equivalent soil structure system.
D=Damping ratio of the fixed base structure
D_x=Horizontal damping ratio of the soil, given (Richart et. al, 1970)

$$D_x = \frac{0.288}{\sqrt{B_x}} \quad (10)$$

Where,

$$B_x = \frac{(7-8\upsilon)}{32(1-\upsilon)\gamma r_o^3} W \quad (11)$$

D_θ=Damping ratio of the soil in rocking mode, given (Richart et. al, 1970)

$$D_\theta = \frac{0.15}{(1+B_\theta)\sqrt{B_\theta}} \quad (12)$$

Where,

$$B_\theta = \frac{3(1-\upsilon)I_\phi}{8\rho r_o^5} \quad (13)$$

I_ϕ=Moment of inertia of the structure about the axis of rocking.

K_e=Equivalent stiffness of the system, kN/m

$$K_e = \frac{1}{F_e} \quad (14)$$

Where,

$$F_e = \left(\frac{1}{K'} + \frac{1}{K_x} + \frac{1}{K_\theta}\right) \quad (15)$$

F_e = Equivalent flexibility in m/kN
K'=Fixed base stiffness of the chimney
K_x=Horizontal soil stiffness
K_θ=Rocking Soil stiffness

3.2 Embedment Correction Factor

The corrections factor due to embedment proposed by Whitman et. al (1972), has been used. The formulae have been extracted from the text by Arya et al. (1984).

Horizontal embedment coefficient

$$\eta_x = 1 + 0.55(2-\nu)\left(\frac{h}{r_0}\right) \quad (16)$$

Rocking embedment coefficient

$$\eta_\theta = 1 + 1.2(1-\nu)\left(\frac{h}{r_0}\right) + 0.2(2-\nu)\left(\frac{h}{r_0}\right)^3 \quad (17)$$

The embedment coefficients also get effected due to damping and hence while considering the embedment effect, the damping ratio gets multiplied by their respective damping factor (Arya et al., 1984).

$$D_x = \frac{0.288}{\sqrt{B_x}}\alpha_x \quad (18)$$

Horizontal damping ratio embedment factor, α_x

$$\alpha_x = \frac{1+1.9(2-\upsilon)\frac{h}{r_o}}{\sqrt{B_x}} \quad (19)$$

Rocking damping ratio embedment factor, α_θ

$$\alpha_\theta = \frac{1+0.7(1-\upsilon)\frac{h}{r_o}+0.6(2-\upsilon)\left(\frac{h}{r_o}\right)^3}{\sqrt{B_\theta}} \quad (20)$$

$$D_\theta = \frac{0.15}{(1+B_\theta)\sqrt{B_\theta}}\alpha_\theta \quad (21)$$

3.3 Effective Shear Modulus

The shear modulus measured by in-situ tests are generally low-strain corresponding shear strain amplitude of less than 0.001. However, it has been found that shearing modulus due to earthquakes reduces by 0.9 to 0.2 of that derived using in-situ tests. As the shear strain of the soil increases during seismic events, the shear modulus decreases. The shear modulus is used in computing stiffness values for footings.

According to Euro code EN 1998-5:2004, if the ground acceleration ratio is equal to or greater than 0.1 g, the shear wave velocity and max. Shear modulus have to be multiplied with the average reduction factor as depicted in Table 1. The same reduction factors are used in the present study for comparison.

***Table 1**: Shear modulus correction factor (EN 1998-5:2004)*

Ground acceleration ratio, α	Damping factor	$\frac{V_s}{V_{s,\max}}$	$\frac{G}{G_{\max}}$
0.10	0.03	0.9(±0.07)	0.80(±0.10)

0.20	0.06	0.7(±0.15)	0.50(±0.20)
0.30	0.1	0.6(±0.15)	0.35(±0.20)

4. Problem Statement

To check for the response of RCC chimney subjected to earthquake force resting on soil strata, SSI with inclusion of modified parameters has been included in the analysis.

The chimney height is taken as 150 m with raft diameter of 18 m and area of shell 8.5 m^2. The time period of vibration for the structure fixed at base and the flexible base period are computed separately. The damping ratio for the flexible base is also calculated and the horizontal acceleration coefficient is calculated using the modified time period and damping ratio. The equivalent lateral force static method (clause 17.1, IS 1893-part 4) of analysis is used to compute the design shear force and design bending moment. The parametric problem has been from the text by Dasgupta and Chowdhury (2008).

Methodology adopted is shown in the APPENDIX at the end with step by step procedure. The properties of different types of soils that are used in study are mentioned in Table 2. The below table is extracted from the research paper presented by Mehta and Gandhi (2008).

***Table 2**: Properties of soil used in the study (Mehta and Gandhi, 2008)*

Velocity of Shear waves m/s	Soil Type	Unit Weight, γ kN/m^3	Poisson's ratio, ν	Shear modulus, G kN/m^2	Elastic Modulus kN/m^2
150	Soft Soil	16	0.49	36700	$14.95X10^4$
300	Stiff (Medium) Soil	20	0.45	183500	$25.84X10^5$
600	Dense Soil	22.4	0.35	822000	$50.53X10^7$
1200	Rock	25.6	0.30	3758900	$30.42X10^7$

5. Results and Discussions

MS Excel spreadsheet is developed to analyze for different responses using the code specified Equivalent Static Lateral Force Method for tall chimneys. The below mentioned tables describes the results of analysis for different responses and hence illustrates the importance of Soil Structure Interaction (SSI) effects on seismic response of tall chimneys when it is struck by a long and a short duration earthquake.

1) It is observed from Table 3 below, that the time period and damping ratio for chimney is more for flexible soil. The time period and damping ratio goes on decreasing as the soil goes on getting stiffer.
2) One of the interesting things that can be observed is that the time period goes on decreasing as the shear velocity increases i.e. for stiffer soils with higher shear velocity the time period values approach nearer to that obtained by fixed base assumption. Hence for shear velocity in excess of 600m/s soil flexibility can be ignored and base can be treated as fixed.
3) Similar trend is observed for damping ratio. It becomes almost equal to 5% for the dense soil i.e. with shear velocity in excess of 600m/s.
4) Due to SSI effect, the design shear force and bending moment are found to reduce by a greater percentage in case of soft soil when compared to fixed base condition. However, for stiffer soils this reduction is very less.
5) Computation with reduced G value leads to further reduction in the shear force and bending moment values as shown in table 4. The reduction is very high in zones of high seismic intensity.
6) Further, the embedment effect is also studied and it is observed that the shear forces and bending moments considering SSI acting on the chimney increases when embedment of the foundation is also considered as shown in Table 5. It can be seen that the stiffer the soil, there is increase in the shear force and bending moment, but the increase becomes almost negligible beyond when shear velocity is 600m/sec. In all the calculations, the zone of the structure has been taken as Zone IV.

***Table3:** % change in base forces with consideration of flexible foundation with respect to fixed foundation (Zone IV)*

Type of soil	Shear wave velocity, Vs (m/s)	Unit weight, γ, (kN/m^3)	Poisson's ratio, ν	Without SSI (Fixed base)				With SSI (Flexible base)				% reduction in base shear
				Time period, T (sec)	Damping Ratio, D	Base shear force, V (kN)	Base moment, M (kN-m)	Time period, T (sec)	Damping Ratio, D	Base shear force, V (kN)	Base moment, M (kN-m)	
Soft soil	150	16	0.49	1.121	0.05	4195.265	213633.8	2.54	0.074	1633.194	83166.482	61.07
Stiff soil	300	20	0.45	1.121	0.05	3416.503	173977.2	1.54	0.055	2406.989	122570.18	29.54
Dense soil	600	22.4	0.35	1.121	0.05	2512.135	127924.4	1.24	0.051	2242.770	114207.73	10.72
Rock	1200	25.6	0.3	1.121	0.05	2512.135	127924.4	1.15	0.050	2440.760	124289.87	2.84

***Table 4**: % change in base forces with consideration of flexible base and reduced G value with respect to fixed foundation (for stiff soil)*

Seismic zone	Zone factor, Z	Without SSI (Fixed base)				With SSI and reduced G value				% reduction in forces
		Time period, T (sec)	Damping Ratio, D	Base shear force, V (kN)	Base moment, M (kN-m)	Time period, T (sec)	Damping Ratio, D	Base shear force, V (kN)	Base moment, M (kN-m)	
II	0.10	1.121	0.05	1423.543	72490.525	1.633	0.0574	941.276	47932.276	33.87
III	0.16	1.121	0.05	2277.669	115984.841	1.754	0.059	1386.948	70627.02	39.10
IV	0.24	1.121	0.05	3416.503	173977.261	1.949	0.0631	1836.461	93517.416	46.24
V	0.36	1.121	0.05	5124.755	260965.891	2.564	0.0768	1965.784	100102.901	61.641

***Table 5**: % increase in base forces with consideration of embedment effect (Zone IV)*

Type of soil	Shear wave velocity, Vs (m/s)	Unit Weight, γ (kN/m³)	Poisson's ratio, ν	Without embedment effect		With embedment effect		% increase in forces
				Base shear force, V (kN)	Base moment, M (kN-m)	Base shear force, V (kN)	Base moment, M (kN-m)	
Soft soil	150	16	0.49	1633.194	83166.482	1713.428	87252.254	4.912
Stiff soil	300	20	0.45	2406.989	122570.186	2499.364	127274.19	3.837
Dense soil	600	22.4	0.35	2242.770	114207.737	2285.254	116371.142	1.894
Rock	1200	25.6	0.3	2440.760	124289.879	2454.230	124975.801	0.551

6. Conclusions

In this research, for determining the effect of SSI, chimney is analyzed taking SSI into consideration and the forces are calculated using Equivalent Static Lateral Force Method the following conclusions can be drawn:

1) The natural time period of the chimney increases when it is supported on a more flexible soil. This increase is very small for stiff soil underneath.
2) The damping ratio of the chimney also increases when the supporting soil is more flexible. Although this increase becomes almost negligible in case of dense soil
3) The base shear decreased more in the case of flexible soil because of the increase in the dynamic parameters such as time period and damping ratio.
4) Computation with reduced G value leads to further reduction in the shear force and bending moment values. The reduction is very high in zones of high seismic intensity.
5) Shear forces and bending moments considering SSI acting on the chimney increases when embedment of the foundation was considered.

All of the above mentioned results intensifies the necessity of the consideration of SSI effect during design. It is also seen that SSI becomes an important parameter in Earthquake Analysis of structures resting on soft soil with shear wave velocity less than 600m/sec. There are no provisions in the Indian code IS 1893: Part4-2005 to account for the damping ratio effect, effective G value and embedment factor effect. It is thus concluded that seismic response of stack like structures like tall chimneys is influenced greatly by soil supporting its base and nature of earthquake excitations striking the base. Overlooking any one of them, can considerably affect the performance of structures during earthquake and lead to devastating effects. There is need to revise Indian code by including guidelines on reduction factor used to assess the effect of embedment of foundation and reduced G value on response of the structure as mentioned in Eurocode EN 1998-5:2004, ASCE 7-10 and several referenced literatures.

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Appendix

Problem Description

The chimney height is 150m with raft diameter of 18m and area of shell 8.5m^2 with moment of inertia 92.5 m^4. The chimney is located in zone IV. Find the design bending moment and shear force for the chimney if it is supported on soil with shear wave velocity of 300m/sec. Take SSI effects (Time period, damping as well as embedment) into consideration with G_{max} and $G_{reduced}$ values.

Other required data is as follows -
Unit weight of soil (γ) = 20kN/m^3
Poisson's ratio (υ) = 0.45
Grade of concrete – M30
$E_{concrete}$ = 3.12 x 10^8 kN/m^2

Weight of the superstructure	W = A x H x γ_c (γ_c – unit weight of reinforced concrete)	31875 kN
Time period of fixed base chimney	$T = C_T\sqrt{\frac{WH}{E_c Ag}}$	1.12126 sec
Flexible Base SSI with damping factor		
Dynamic shear modulus, Gmax	$(G = \rho V_s^2)$	183486.24 kN/m^2
Fixed base stiffness of chimney	$K' = \frac{4\pi^2 W}{gT^2}$	102028.7741 kN/m
Horizontal soil stiffness	$K_x = \frac{32(1-\nu)Gr_o}{(7-8\nu)}$	8548300.054 kN/m
Rocking soil stiffness	$K_\theta = \frac{8Gr_o^3}{3(1-\nu)}$	648540450.40 kN/m
Effective time period	$T' = T\sqrt{1+\frac{K'}{K_x}\left(1+\frac{K_x \hbar^2}{K_\theta}\right)}$	1.544 sec
Horizontal soil damping	$D_x = \frac{0.288}{\sqrt{B_x}}$	0.4431
Rocking soil damping	$D_\theta = \frac{0.15}{(1+B_\theta)\sqrt{B_\theta}}$	8.422
Equivalent flexibility	$F_e = \frac{1}{K} + \frac{1}{K_x} + \frac{1}{K_\theta}$	9.919 X 10^{-6} m/kN
Equivalent stiffness	$K_e = \frac{1}{F_e}$	100809.6942 kN/m
Flexible base damping ratio	$D' = K_e\left(\frac{D}{K'} + \frac{D_x}{K_x} + \frac{D_\theta}{K_\theta}\right)$	0.0559
Sa/g	1.36/T (Medium soil)	0.8806
Damping factor	Damping % / Factor: 5 / 1; 7 / 0.9	0.970
Modified Sa/g	Sa/g x damping factor	0.8545
Horizontal seismic coefficient	$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$	0.05127
Design shear force at the base	$V = C_v A_h W_t D_v$	**2406.909 kN**
Design Bending moment at the base	$M = A_h W_t \hbar D_m$	**122570.186 kN-m**
Flexible base SSI with reduced Shear modulus and damping factor		
Ground acceleration ratio	Zone 4	0.24
Average reduction factor	Ground acceleration ratio, α / $\frac{G}{G_{max}}$: 0.1 / 0.8; 0.2 / 0.5; 0.3 / 0.35	0.44
Reduced dynamic shear modulus of soil	G_{max} X average reduction factor	81467.89 kN/m^2
Horizontal soil stiffness	$K_x = \frac{32(1-\nu)Gr_o}{(7-8\nu)}$	3795445.224 kN/m
Rocking soil stiffness	$K_\theta = \frac{8Gr_o^3}{3(1-\nu)}$	287951960 kN/m
Effective time period	$T' = T\sqrt{1+\frac{K'}{K_x}\left(1+\frac{K_x \hbar^2}{K_\theta}\right)}$	1.949 sec
Horizontal soil damping	$D_x = \frac{0.288}{\sqrt{B_x}}$	0.443
Rocking soil damping	$D_\theta = \frac{0.15}{(1+B_\theta)\sqrt{B_\theta}}$	8.422
Equivalent flexibility	$F_e = \left(\frac{1}{K'} + \frac{1}{K_x} + \frac{1}{K_\theta}\right)$	1.0068 x 10-5 m/kN

Equivalent stiffness	$K_e = \frac{1}{F_e}$	99323.574
Flexible base damping ratio	$D' = K_e(\frac{D}{K'} + \frac{D_x}{K_x} + \frac{D_\theta}{K_\theta})$	0.0576
Sa/g	$1.36/T$	0.697
Correction factor for damping	Damping % — Factor 5 — 1 7 — 0.9	0.0631
Sa/g modified	*Sa/g x damping factor*	0.651
Horizontal seismic coefficient	$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$	0.0391
Design Shear Force at the base	$V = C_v A_h W_t D_v$	1836.461 kN
Design Bending moment at the base	$M = A_h W_t \hat{h} D_m$	93517.413 kN-m
Flexible base SSI with embedment correction		
Depth of foundation below ground	h	3 meter
Horizontal embedment coefficient	$\eta_x = 1 + 0.55(2-\nu)\left(h/r_0\right)$	1.2841
Rocking embedment coefficient	$\eta_\theta = 1 + 1.2(1-\nu)\left(h/r_0\right) + 0.2(2-\nu)\left(h/r_0\right)$	1.23
Horizontal soil stiffness	$K_{x,emb} = \frac{32(1-\nu)Gr_0}{(7-8\nu)}\eta_x$	10977441.99 kN/m
Rocking soil stiffness	$K_{\theta,emb} = \frac{8Gr_0^3}{3(1-\nu)}\eta_\theta$	798665554.6 kN/m
Effective time period	$\tilde{T} = T\sqrt{1 + \frac{k}{K_{x,emb}}\left(1 + \frac{K_{x,emb}\hat{h}^2}{K_{\theta,emb}}\right)}$	1.474
Horizontal embedment factor	$\alpha_x = \frac{1 + 1.9(2-\nu)\frac{h}{r_o}}{\sqrt{B_x}}$	1.748
Horizontal soil damping	$D_x = \frac{0.288}{\sqrt{B_x}}\alpha_x$	0.774
Rocking embedment factor	$\alpha_\theta = \frac{1 + 0.7(1-\nu)\frac{h}{r_o} + 0.6(2-\nu)(\frac{h}{r_o})^3}{\sqrt{B_\theta}}$	1.047
Rocking soil damping	$D_\theta = \frac{0.15}{(1+B_\theta)\sqrt{B_\theta}}\alpha_\theta$	7.952
Equivalent flexibility	$F_e = (\frac{1}{K'} + \frac{1}{K_x} + \frac{1}{K_\theta}$	$9.893 \text{ X } 10^{-6}$ m/kN

Equivalent stiffness	$K_e = \frac{1}{F_e}$	101076.4167 kN/m
Flexible base damping ratio	$D' = K_e(\frac{D}{K'} + \frac{D_x}{K_x} + \frac{D_\theta}{K_\theta})$	0.0576
Sa/g	1.36/T	0.9227
Correction factor for damping	Damping % — Factor 5 — 1 7 — 0.9	0.9616
Sa/g modified	Sa/g x damping factor	0.887
Horizontal seismic coefficient	$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$	0.0532
Design Shear Force at the base	$V = C_v A_h W_t D_v$	**2499.364 kN**
Design Bending moment at the base	$M = A_h W_t \hat{h} D_m$	**127274.190 kN-m**