ASPS Conference Proceedings 1: 575-581 (2022)

Proceedings of

12th Structural Engineering Convention - An International Event (SEC 2022)

Available at https://asps-journals.com/index.php/acp

A Simplified Approach for Analysis of MDOF Systems Considering Soil - Structure Coupling

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Paper ID - 060006

Abstract

It is common to design structures on the fundamental assumption that the base is fixed and that the ground motion experienced by its base is the same as the free-field ground motion. For structures supported on soft soil, the base motion experienced by the structure is generally different from the free-field motion, as it could include possible sliding and rocking motion of the flexible medium and dissipation of vibration energy through the soil in the form of damping. The seismic response of a structure at a particular location depends on the characteristics of ground motion at source, and; modified mode shapes and vibration periods because of soil structure coupling. Thus, the ground motion that reaches the foundation can be significantly different from that at bedrock level and there is a possibility of response amplification when vibration period of the structure is close to that of the input ground motion modified by local soil conditions. Soil Structure Coupling (SSC) is a process wherein the structure and its supporting soil medium interact with one another to influence the behaviour of both. SSC normally leads to an increase in natural period of the structure, increased damping and an increase in lateral displacements of the structure. The effect of SSC is commonly ignored, because it is often a valid assumption. However, such effects can, in particular circumstances, be detrimental to the structure. The paper presents a simplified procedure for finding out the response of three-storey structure due to the effect of SSC. A simple practical method to assess the likely impact of SSC on the response of a MDOF structure is presented, which can help the researchers understand the detailed behaviour of soil and structure during seismic events. Detailed step-by-step procedure is presented by solving a numerical problem.

Keywords: Soil structure interaction, sub-soil parameters, soil liquefaction, multi-degree of freedom system

1. Introduction

In dynamic analysis of a building under seismic conditions, its base is considered to be fixed and subjected to the free-field ground motion. Such ground motion is not influenced by presence of the structure. This is applicable to rock formations because due to the extremely high stiffness of rock, seismic wave motion therein is not constrained by the structure supported thereon. However, if the structure is supported on soft soil of considerable thickness overlying the rock, then the structure and soil will interact with one another to influence the behaviour of both. This is termed as soil structure coupling (or interaction) and it creates a new dynamic system. As earthquake induced ground motion traverses from its origin to the bedrock underlying a building; it undergoes modifications due to the source effect, path effect and local site effects.

The paper describes the simple practical method to assess the likely impact of SSC on the response of a MDOF structure, assuming that the soil is not liquefiable.

2. Parameters of Strong Ground Motion

Ground motion during an earthquake is composed of pulses which are random in frequency, amplitude and duration. Earthquake induced ground motion can be captured in terms of displacement, acceleration or velocity. It can be synthesized into two orthogonal and one vertical component plus two rocking and one torsional component. The two horizontal components are normally considered for structural design since they are often the predominant cause for building damage. With the limited dimensions of common building structures, the spatial variation in ground motion generally does not affect their seismic performance.

Notwithstanding this broad observation, there is no accepted principle to relate the likely extent of building damage to an earthquake's signature. The damage experienced by a building is a function of (i) peak ground acceleration (PGA) (ii) duration of motion (iii) frequency content of ground motion (iv) natural frequency of the structure (v) characteristics of the soil on which the structure is supported (vi) degree of structural and soil damping, and other factors. Under the circumstances it is a specialized geotechnical exercise to select an appropriate earthquake signature for design.

In spite of the highly sophisticated techniques available to predict the influence of all these factors on ground motion; the characteristics of ground motion as it may prevail at a given site can, at best, be an informed guess.

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Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India | 19-22 December, 2022

Published online: December 19, 2022

doi:10.38208/acp.v1.551

Some of the important ground motion parameters as far as they relate to interaction of the soil with a building structure are (i) amplitude and frequency content (ii) effective duration of strong motion, and (iii) time history of motion.

3. Important Sub - Soil Parameters

The response of a building supported on compliant soil depends on characteristics of the soil intervening between building foundation and underlying bedrock. It plays a significant role in the magnitude of damage that an earthquake, of a particular signature, can cause. An important consideration in design is to obtain properties of soil such as stiffness, damping, density and others which affect dynamic soil-structure interaction. Of these properties, the first two play an important role in a structures' response and density in liquefaction potential.

In-situ soils are commonly anisotropic and non-homogeneous. Their behaviour is nonlinear and their properties can only be ascertained within a broad band because of problems in sampling, testing and interpretation of results. Field tests have the advantage that they do not require sampling which could alter the chemical and structural conditions of soil. There are many methods available to determine soil properties, each with their own advantages and limitations. Some of the important soil parameters that could affect seismic response of a building, are (i) depth of soil overlay and its stratification, (ii) dynamic shear modulus (g), (iii) Poisson's ratio, (iv) particle grain size distribution, (v) soil damping, (vi) relative density, (vii) water depth, and (viii) soil bearing capacity.

4. Soil Liquefaction

Liquefaction could lead to lateral spreading of soil, loss of bearing capacity which may cause the structure to tilt, settle or overturn. It can also induce differential settlements between foundations and create enhanced lateral pressures on retaining walls. Light structures can experience uplift. There have been many dramatic structural failures as a consequence of liquefaction of subsoil.

5. Soil Structure Coupling (SSC)

The seismic response of a structure at a particular location depends on many factors such as, (i) characteristics of ground motion at source, (ii) filter function of the intervening media from source to the site – i. e. effects of wave attenuation etc., (iii) modifications to input motion due to nature and extent of soil overburden on the underlying rock. Soil layers in the overburden can filter some or amplify other frequencies of incoming ground waves. Thus, the ground motion that reaches the foundation can be significantly different from that at bedrock level, (iv) modified mode shapes and vibration periods because of soil structure coupling, (v) possible response amplification when vibration period of the structure is close to that of the input ground motion modified by local soil conditions, and (vi) a significant portion of the vibration energy may be dissipated through material and radiation damping of the soil supporting medium.

SSC is a process wherein the structure and its supporting soil medium interact with one another to influence the behaviour of both. For example, when a rigid foundation rests on a soft soil medium then it will influence the free-field ground motion. At the same time, deformation of the ground will affect the response of the structure. SSC normally leads to an increase in natural period of the structure, increased damping, and an increase in lateral displacements of the structure.

The degree of these increases depends, among other factors, on mass of the structure, on stiffness of the soil and that of the structure, and natural period of vibration of the structure. It is common to assume the input motion at base of a building structure to be the same as the free-field motion i. e. the effect of SSC is commonly ignored. This is probably because it is often a valid assumption plus the usual presumption that such effects are beneficial as they lengthen the period of vibration and enhance damping. However, such effects can, in particular circumstances, be detrimental to the structure [5].

6. Dynamics of Soil-Structure Coupling

Normally, in dynamic analysis the base is assumed as fixed which can be considered as realistic only if the building is supported on solid rock or when the stiffness of subsoil is very high in comparison with that of the superstructure. Conditions under which the impact of SSC should be allowed for in design can at best be described in a general way as:

(a) for structures where P-Δ effect can play a significant role.
(b) where the foundations are massive and deep.
(c) for tall slender structures.
(d) where the supporting soil layer is both very soft (average shear wave velocity < 100 m/s) and of considerable depth.
(e) in cases where the supporting piles pass through alternating very stiff and very soft soil layers.

Dynamic soil structure coupling can be distinguished in two forms viz. (i) kinematic - which is due to difference in stiffness between soil and structure and (ii) inertial - which is due to the mass of the structure.

6.1 Kinematic Interaction

Due to an earthquake, the soil undergoes motion. When such movements are not influenced by the presence of any structure, they are known as free-field motions. A rigid foundation does not mimic the free-field motion and there is a slip at the soil-foundation interface. As a result, the input motion gets modified and this is known as kinematic interaction.

The actual motion input into the foundation depends on its geometry and its relative stiffness with respect to the soil. This is a complex phenomenon with no simple solution to evaluate its effect. Tall buildings often have massive multi-level deep basements which form a box. In such cases, the building will be excited by motion of the basement [6] rather than that of the free-field soil. However, for normal building structures it is common to consider the input as the free-field motion unless the structure is massive or is very important.

6.2 Inertial Interaction

The mass of a structure induces inertia forces and causes the super structure to vibrate. In doing so, it transmits inertial forces, in the form of base shear and moment, to the soil. If the supporting soil is compliant, then dynamic interactions, in the form of displacements and rotations, occur at the base level and these influence the final response of the structure. This is termed as inertial interaction. While the soil adjacent to the foundation vibrates, some quantity of energy from the soil is lost in moving the soil mass.

6.3 Evaluating Effect of Soil Structure Coupling

For structures supported on soft soil, the base motion experienced by the structure is generally different from the free-field motion as it could include:

(a) possible sliding and rocking motion of the flexible medium
(b) dissipation of vibration energy through the soil in the form of material damping and radiation damping.
(c) effects of foundation stiffness
(d) extent of foundation embedment in the supporting medium.

There are various methods available to evaluate the impact of soil structure coupling. The two general approaches [6] for a soil - structure analysis are categorized as (i) direct approach and (ii) substructure approach. All methods suffer from a basic problem of uncertainties associated with the dynamic properties to adopt for soil. In the discussion below, the effect of foundation embedment is not considered.

Direct Approach

In this approach, the soil (in the near field) and the structure together with its foundation are modeled and analysed as a single system as shown in Fig. 1.

For this purpose, normally FEM may be used. Herein, the properties of the embedded footings as well as the variation in properties of soil layers can be accounted for. However, to incorporate the effect of damping, there is a need to incorporate absorbing / transmitting boundary elements so that the total energy is not trapped inside the model. This permits simulation of the seismic energy radiating away from the problem domain. In this approach, the model size becomes very large and the approach is computationally expensive. Secondly, if there is a change, in say the superstructure, the entire analysis would have to be repeated.

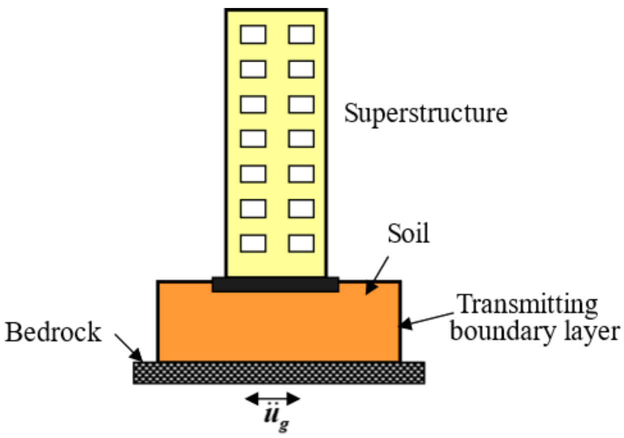

Fig. 1. Direct Approach

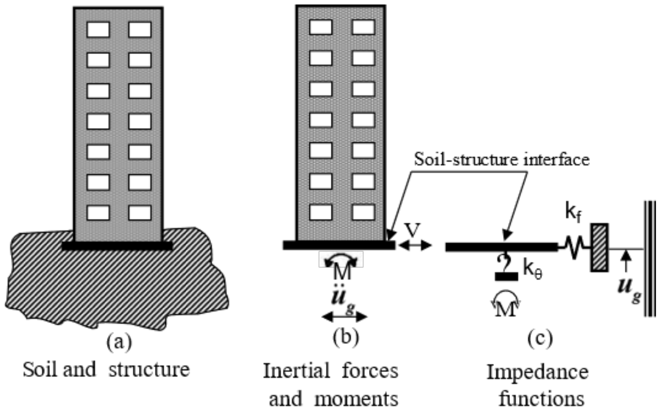

Fig. 2. Sub-structure Approach

Substructure Approach

In this approach, the soil and structure (Fig 2a) are modeled separately. The structure is idealized through a finite element grid and the base shear and moment are obtained (Fig 2b). Subsequently the soil is discretized with the help of Winkler springs which can model horizontal, rocking and other impedance functions of the soil. Dashpots may be used for viscous damping (Fig 2c). The two models are connected by imposing compatibility conditions along the foundation and soil interface.

Both the above methods involve extensive complex modeling and analysis. The method described below is a simplified approach which can give a reasonable insight into the effect of SSC for buildings where the primary response is from the first mode.

7. Simplified Method for a MDOF System [4]

The method described below can be conveniently used to ascertain the approximate effect of SSC on the response of a MDOF system, where the first mode response is predominant. The MDOF system vibrating in the first mode is replaced by an equivalent SDOF system with a mass equal to that of the first mode as given by Eq. (1).

$$M_i = \frac{\left[\sum_{j=1}^{N} m_j \varphi_{ji}\right]^2}{\sum_{j=1}^{N} m_j \left(\varphi_{ji}\right)^2} \tag{1}$$

Thus, the SDOF system will have a lumped mass equivalent to the modal mass for the first mode of the MDOF system. The height h_1 of the equivalent SDOF oscillator specialised for the first mode is obtained from

$$h_1 = \frac{\sum_{j=1}^{N} m_{j1}\varphi_{j1}h_j}{\sum_{j=1}^{N} m_{j1}\varphi_{j1}} \tag{2}$$

where

m_{j1} : seismic mass at node j in the first mode
φ_{j1} : displacement amplitude of the first mode at node j
h_j : height of node j above the base

h_1 : height of the mass of the equivalent oscillator above the base.
The vibration period of the oscillator equivalent to the first mode of the MDOF system is given by:

$$\tilde{T}_1 = T_1\sqrt{1+\tilde{k}_1\left[\frac{1}{k_f}+\frac{h_1^2}{k_\theta}\right]}$$

(3)
where

$$\tilde{k}_1 = 4\pi^2\left(\frac{M_1}{T_1^2}\right) \quad (4)$$

and M_1 and T_1 are modal mass and period of the fundamental mode of the MDOF system.

Once the vibration period of the equivalent SDOF system $\tilde{T}_1$ is obtained, the horizontal acceleration can be read from codal stipulations which will provide the modified first mode base shear $\tilde{V}_1$ using the modified damping value $\tilde{\xi}$. ASCE 7-05 [1] places a restriction that $\tilde{V}_1$ shall in no case be < 0.7 V_1 where V_1 is the first mode base shear for the fixed base MDOF structure.

Steps involved in the analysis process to determine the approximate effect of SSC for a MDOF system; are listed below:
1. After a detailed geotechnical investigation, obtain soil parameters k_f and k_θ
2. Using the modal analysis technique, undertake a eigenvalue analysis which will provide values of frequencies ω_i, time periods T_i, mode shapes φ_{ji}
3. For each mode, determine modal masses M_i, modal floor masses (m_{ji}) and modal participation factors P_i.
4. From codal design response spectrum, [3] read off acceleration coefficient S_{ai}/g corresponding to each modal time period T_i
5. Determine horizontal seismic coefficient A_{hi} followed by lateral storey forces Q_{ji} and base shears V_i
6. With values of Q_{j1} for the first mode, determine the base moment M_{b1} for this mode which is given by

$$M_{b1} = \sum Q_{j1}h_j$$

7. Determine floor displacements u_{ji} for each mode based on storey shear forces Q_{ji} and the stiffness matrix.
8. For the oscillator equivalent to the first mode of the MDOF system, evaluate equivalent height h_1 from Eq. (2).
9. For the equivalent oscillator with SSC, determine stiffness $\tilde{k}$ from Eq. (4), and first mode time period ($\tilde{T}_1$) using Eq. (3).
10. For the time period $\tilde{T}_1$ read off the acceleration coefficient Sa/g from the response spectrum and then arrive at the acceleration coefficient $\tilde{A}_{h1}$ for 5% damping
11. Calculate equivalent damping ($\tilde{\xi}_1$) utilizing Eq. (5).

$$\tilde{\xi} = \left[\frac{\xi_s}{k_s}+\frac{\xi_f}{k_f}+\frac{\xi_\theta h^2}{k_\theta}\right] \Big/ \left[\frac{1}{k_s}+\frac{1}{k_f}+\frac{h^2}{k_\theta}\right] \quad (5)$$

12. Modify value of $\tilde{A}_{h1}$ in step 10 for the increased stiffness damping ($\tilde{\xi}_1$) due to SSC taking values from IS 1893.

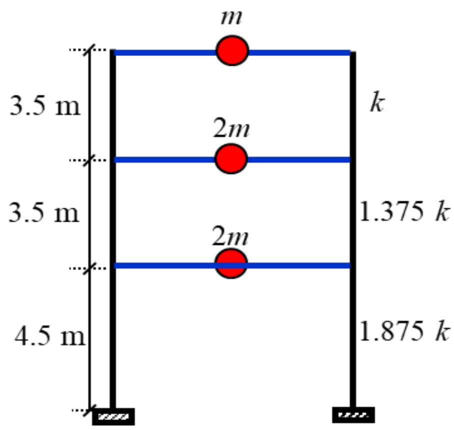

Fig. 3. Three-Story Case-Study Frame

13. Obtain base shear of the oscillator equivalent to the first mode of vibration of the MDOF structure by the equation

$$\tilde{V}_1 = \tilde{A}_{h1}\ M_1\ g \quad (6)$$

14. Check that $\tilde{V}_1 > 0.7V_1$. If not, the value $\tilde{V}_1$ needs to be enhanced accordingly.
15. Obtain total base shear for the MDOF structure with SSC by SRSS method. First mode base shear being taken as $\tilde{V}_1$ and values for other modes being included in the summation without any modification for SSC.
16. The modified lateral deflection at floor j in the fundamental mode '1' taking SSC into account (i.e. $\tilde{u}_{j1}$) is then obtained as,

$$\tilde{u}_{j1} = \frac{\tilde{V}_1}{V_1}\left[\frac{M_{b1}h_j}{k_\theta}+u_{j1}\right] \quad (7)$$

where
M_{b1}: overturning base moment for the fundamental mode of the fixed base structure using the unmodified modal floor forces determined in step 5
h_j : height of storey j above the base
u_{j1} : lateral deflection of floor j for the fundamental mode as for the fixed base structure using the unmodified modal base shear V_1 as obtained in step 7.
17. This deflection in step 16 is to be combined by the SRSS method with deflections for higher modes obtained in step 7. These are to be included without modification for SSC.

8. Application to MDOF system

The process of evaluating base shear including soil structure coupling (SSC) by the simplified method is explained below. For a 3-DOF frame of dimensions with mass and stiffness parameters as shown in Fig. (3), the following data is provided:

Structural parameters:
m = 120,000 kg
k = 5500 kN/m
Seismic zone (Z) = IV
Importance factor (I) =1
Response reduction factor (R) = 5
Damping ξ_s = 5%

Soil parameters:
k_f = 225,000 kN/m
k_θ =1800,000 kNm/radian
Damping ξ_f =10%
ξ_θ =15%.
It is required to calculate the base shear and lateral displacement of the roof, taking soil structure coupling into account.

(a) *Fixed-base MDOF system* [2]

Consider the fixed-base structure shown in Fig (3), supported on soft soil as per the given data.

(i) *Base shear*
The mass and stiffness matrices are:

$$\boldsymbol{M} = m\begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \text{ and } \boldsymbol{K} = k\begin{pmatrix} 3.25 & -1.375 & 0 \\ -1.375 & 2.375 & -1 \\ 0 & -1 & 1 \end{pmatrix} \quad (8)$$

Solving the eigen problem, the three frequencies and time periods are as under:

ω_1 = 3.140 rad/sec, T_1 = 2.0 sec
ω_2 = 7.746 rad/sec, T_2 = 0.811 sec
ω_3 = 10.241 rad/sec, T_3 = 0.614 sec.

The modal matrix is:

$$\begin{pmatrix} 0.382720 & -0.672615 & 1.335355 \\ 0.784834 & -0.309080 & -1.288253 \\ 1.000000 & 1.000000 & 1.000000 \end{pmatrix}$$

(9)
Modal masses in each mode are obtained from Eq. (10).

$$M_i = \frac{\left[\sum_{j=1}^{N} m_j \varphi_{ji}\right]^2}{\sum_{j=1}^{N} m_j \left(\varphi_{ji}\right)^2} \quad (10)$$

Substituting values, the modal mass for the first mode will be

$$M_1 = \frac{\left[(240\times 0.382720)+(240\times 0.784834)+(120\times 1)\right]^2 \times 10^3}{(240\times 0.382720^2)+(240\times 0.784834^2)+(120\times 1^2)}$$

$$= 528.64 \times 10^3 \text{ kg} \quad (11)$$

Similarly, modal masses for all modes are evaluated and these are presented in Table (1).

Table 1. Modal Mass and Story Shear for all Modes

Mode	T (sec)	Sa/g	A_h	Mass (kg)	V (kN)
1	2.000	0.835	0.02004	5,28,640	103.926
2	0.811	2.059	0.04944	53,137	25.773
3	0.614	2.500	0.06000	18,223	10.726

Base shear for each mode is given by $V_i = A_{hi} \times M_i \times g$
Introducing values of A_h and modal mass M for first mode from Table (1), base shear for the first mode is,

$$V_1 = 0.02004 \times 528{,}640 \times 9.81 \times 10^{-3} = 103.926 \text{ kN.} \quad (12)$$

Proceeding accordingly, base shears for the other two modes are obtained and are given in Table (1). Combining these modal values by SRSS method, the total base shear for the fixed base structure is,

Base shear =

$$\sqrt{103.926^2 + 25.773^2 + 10.726^2} = 107.610 \text{ kN} \quad (13)$$

(ii) *Modal Floor masses*

Participation factors for the three modes are obtained using Eq. (14).

$$P_i = \frac{\sum_{j=1}^{N} m_j \varphi_{ji}}{\sum_{j=1}^{N} m_j \left(\varphi_{ji}\right)^2} \quad (14)$$

Substituting values in this equation, the first mode participation factor is,

$$P_1 = \frac{(240 \times 0.382720)+(240 \times 0.784834)+(120 \times 1)}{(240 \times 0.382720^2)+(240 \times 0.784834^2)+(120 \times 1^2)} \quad (15)$$
$$= 1.3209$$

Similarly, participation factors for the other modes will be,
P_2 = - 0.459658 , P_3 = 0.138792
The modal mass (m_{ji}) at floor j in mode i will be, $m_j \varphi_{ji} P_i$
Substituting values, the modal mass at floor 1 in mode 1 will be,
m_{11} = 240,000 × 0.382720 ×1.3209 = 121.328 ×10^3 kg (16)
Modal floor masses for first mode are:

m_{11} = 121.3283 × 10^3 kg
m_{21} = 248.8047 × 10^3 kg
m_{31} = 158.5079 × 10^3 kg

(iii) *Storey Shear Forces*

For the given data viz Zone IV, importance factor of 1.0 and with a response reduction factor of 5;

$$A_h = \frac{Z}{2} \cdot \frac{I}{R} \cdot \frac{S_a}{g} \quad (17)$$

from Eq. (17), the seismic horizontal coefficient is

$$A_h = 0.024\ S_a/g \quad (18)$$

Reading off values for *Sa/g* from codal response spectrum for each modal time period evaluated earlier, the A_h values for each mode are obtained and presented in Table (1).
Story force for floor j in mode i will be

$$Q_{ji} = A_{hi}\ m_j\ \varphi_{ji}\ P_i\ g \quad (19)$$

which for the first mode is,

$Q_{11} = 0.02004 \times 121.3283 \times 10^3 \times 9.81/\ 1000 = 23.852$ kN

(20)

Similarly, forces are evaluated for the other two modes and listed in Table (2).

Table 2. Story Shear in Three Modes

Storey	Mode		
Force (kN)	1	2	3
Q_1	23.852	35.988	26.181
Q_2	48.913	16.537	-25.258
Q_3	31.161	-26.752	9.803

(iv) *Base Moment for First Mode*

Moment of storey forces about the base in the first mode is obtained by

$$M_{b1} = \sum_{1}^{3} Q_{j1} h_j \tag{21}$$

Utilising values of storey forces for the first mode from Table (2) and storey heights from Fig. (3),

Base moment M_{b1} =

$$(31.161 \times 11.5) + (48.913 \times 8.0) + (23.852 \times 4.5) = 857 \text{ kNm} \tag{22}$$

(v) *Floor Displacements*

Floor displacements will be given by,

$$[\boldsymbol{U}] = [\boldsymbol{K}]^{-1}[\boldsymbol{Q}] \tag{23}$$

Substituting values for the first mode,

$$\begin{bmatrix} u_{11} \\ u_{21} \\ u_{31} \end{bmatrix} = \begin{pmatrix} 17875.0 & -7562.5 & 0 \\ -7562.5 & 13062.5 & -5500.0 \\ 0 & -5500.0 & 5500.0 \end{pmatrix}^{-1} \begin{bmatrix} 23.852 \\ 48.913 \\ 31.161 \end{bmatrix} = \begin{bmatrix} 10.078 \\ 20.666 \\ 26.332 \end{bmatrix} \times 10^{-3} \text{ m}$$

Proceeding similarly for the other modes; roof deflections for modes 1, 2 and 3 are

u_{31} = 26.332 mm
u_{32} = -3.716 mm
u_{33} = 0.779 mm

(b) *Equivalent First Mode SDOF system with SSC*

For the MDOF structure under consideration, we need to arrive at the equivalent oscillator for the first mode. Utilising Eq. (2); height of such a system is

$$h_1 = \frac{(158.508 \times 11.5) + (248.804 \times 8) + (121.328 \times 4.5)}{528.64} = 8.246 \text{ m}$$

From Eq. (4), the equivalent oscillator stiffness is

$$\tilde{k}_1 = M_1 \omega_1^2 = 528.64 \times 10^3 \times 3.14^2 / 1000 = 5212 \text{ kN/m}$$

Vibration period of the equivalent oscillator with SSC is obtained by substituting values in Eq. (3).

$$\tilde{T}_1 = 2.0 \times \sqrt{1 + 5212 \left\{ \frac{1}{225{,}000} + \frac{8.246^2}{1800{,}000} \right\}} = 2.21 \text{ sec}$$

For this time period; from the codal response spectrum, S_a/g = 0.756 for 5% damping

Equivalent Damping

Substituting values in Eq. (5), the equivalent damping is given by,

$$\tilde{\xi} = \frac{\left[\frac{5}{5212} + \frac{10}{225{,}000} + \frac{15 \times 8.246^2}{1800{,}000} \right]}{\left[\frac{1}{5212} + \frac{1}{225{,}000} + \frac{8.246^2}{1800{,}000} \right]} \times 10^{-2} = 6.71\%$$

Substituting values in Eq. (17), the horizontal seismic force coefficient is,

$$\tilde{A}_{h1} = 0.024 \times 0.756 = 0.018$$

Base shear of the equivalent oscillator with SSC corresponding to the first mode of the MDOF system is,

$$\tilde{V}_1 = (528.640 \times 0.018 \times 9.81) = 93.35 \text{ kN}$$

$\tilde{V}_1$ (93.354 kN) > 0.7 V_1 (0.7 × 103.926 = 72.75 kN)

Hence safe.

This modified first mode base shear value $\tilde{V}_1$ is now combined with base shear values for the other two modes for a fixed base structure without SSC. The total base shear with SSC will be,

Base shear (with SSC) =

$$\sqrt{93.35^2 + 25.773^2 + 10.726^2} = 97.43 \text{ kN}$$

Roof displacement in the first mode is obtained by substituting values in Eq. (7),

$$= \frac{93.35}{103.926} \left[\frac{857 \times 11.5}{1800000} + 26.332 \right] = 23.657 \text{ mm}$$

Combining this value with roof displacement values for other two modes calculated earlier,

Roof displacement =

$$\sqrt{23.657^2 + (-3.716)^2 + 0.779^2} = 23.96 \text{ mm}$$

9. Conclusion

The paper presents a simplified procedure for finding the response of three-storey structure due to the effect of SSC. A simple practical method to assess the likely impact of SSC on the response of a 3-DOF structure is presented. This will help the researchers understand the detailed behaviour of soil and structure during seismic events. Detailed step-by-step procedure is presented by solving a numerical problem, which will support in understanding the effect of different parameters on the structural response. Researchers can obtain approximate results of dynamic analysis using response spectrum method, considering effect of soil-structure coupling. These results will give tentative values, which can be compared with the software results.

Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

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