Manipal Journal of Science and Technology

Volume 7 | Issue 2 Article 5

12-1-2022

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Recommended Citation

Kamal, Smit (2022) "A simple technique to obtain the response of a structure considering soil-structure interaction (SSI)," *Manipal Journal of Science and Technology*: Vol. 7: Iss. 2, Article 5.
Available at: https://impressions.manipal.edu/mjst/vol7/iss2/5

Research Article

A simple technique to obtain the response of a structure considering soil-structure interaction (SSI)

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Abstract

In the conventional analysis of structures, the effect of soil-structure interaction (SSI) is generally neglected. Analysis of the structures without considering the effect of SSI may not be a realistic approach for all the cases particularly when structures are subjected to forces due to earthquakes. One of the limitations of SSI consideration in the analysis is due to the complexity involved in such analysis and this is the main reason for neglecting SSI in the analysis. In this paper, an alternative method for obtaining a structure response that is similar to a structure taking SSI is proposed. In this approach, the time period of the structure resting on soil is determined in the first step and in the second step, the response of the structure with a similar time period but fixed at the base is obtained. The response of this fixed base structure, without considering SSI is more or less similar to the response of the structure considering SSI.

Keywords: soil-structure interaction (SSI), earthquake ground motion, seismic response, fixed base structure, time period, finite element method (FEM).

1. Introduction:

In the conventional analysis and design of superstructure and foundation, the superstructure is assumed as fixed or hinged at the bottom and its behavior is assumed to be completely independent of the foundation supporting soil. The foundation is assumed to be stiff and contact pressure distribution is assumed to be uniform or linearly varying. The stiffness of the foundation and structure is not taken into account. It is known that the behavior of a superstructure and its foundation relies on the stiffness of the superstructure, foundation, and soil system. Superstructure, foundation, and supporting soil are integral units of load carrying system and for proper evaluation of differential settlement and forces in superstructure and foundation, it is necessary to consider them as a part of a single system. For the proper analysis of structure supported on soil and subjected to earthquakes, the superstructure, footing, and supporting soil need to be considered as one system. Analysis of superstructure, foundation, and soil by considering the interaction between them is realistic and the analysis is called soil-structure interaction (SSI) analysis. The finite element method (FEM) can be used to analyze such problems and there are several methods each utilizing different mathematical models that have been used to analyze SSI problems.

Until recently, engineers and researchers generally agreed that soil SSI effects are advantageous to the response of structures because SSI gives the structural systems more flexibility and damping (Ucak and Sopelas[1]). The recent investigations, however, showed that the SSI may not be beneficial in all cases (Chaudhary et al.,[2]; Requena-Garcia-Cruz et al.,[3]; Tongaonkar and Jangid [4]; Spyrakos and Loannidis[5]; Zhenyun et al.,[6]; Shinyoung and BuSeog[7]; Shahrzad[8]). These studies demonstrate the significance of including SSI in seismic force analysis of structures. However, since the dynamic analysis requires the calculation of the response of a structure at various time intervals, the analysis is more complex and requires a larger time when FEM is used to model the structure since modeling requires consideration of structure, foundation, and

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Manuscript received: 20-09-2022

Revision accepted: 28-10-2023

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How to cite this article: Smit Kamal, “A simple technique to obtain the response of a structure considering soil-structure interaction”, Manipal J. Sci. Tech., vol.7(2), 23-27, 2022.

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soil as one unit. Hence, an alternative approach that will not require the calculation of response at every time interval for the structure considering the soil and foundation in finite element modeling is proposed in this study. This approach, however, requires a time period for the structure that considers the foundation and soil in FEM modeling. Once the time period for the structure considering the SSI effect is determined, consideration of SSI is not required to obtain the structure response at every time interval. This approach assumes that the response of the fixed base structure, without considering the soil in finite element modeling is almost similar to the structure response obtained by considering the effect of soil in finite element modeling. However, the time period of the fixed base structure is to be similar to the time period of the structure resting on soil mass. Thus, responses in this method can be calculated using the fixed base structure having a time period similar to the time period of the structure with soil mass. Hence this approach avoids the complexity involved in modeling the superstructure, footing, and supporting soil in the SSI analysis to obtain the response. The applicability of the proposed method is demonstrated with an example of a continuous bridge structure.

2. Modeling of continuous bridge considered for the analysis

As already mentioned, the proposed analysis involves two parts. In the first part, the time period of the structure is obtained considering the structure, foundation, and soil in finite element discretization and in the second part, the structure response fixed at the base having a time period similar to the time period of the structure considering SSI is obtained.

2.1. FEM modeling of the continuous bridge to determine the time period

The FEM model of the continuous bridge, foundation, and soil system is shown in Figure 1. Superstructure between the supports and each pier is modeled using two noded plane frame elements with three degrees of freedom at each node and is considered as an element interconnected at the joints. Soil is considered an elastic continuum and the foundation beneath the pier and soil medium are modeled as an assemblage of four noded plane strain elements with two translational degrees of freedom. The soil mass is resting on the bedrock and hence all the nodes at the base of the soil are considered as fixed. To simulate an infinite soil medium, Kelvin elements with spring and dashpot presented by Novak and Mitwally[9] are attached to the side walls of the soil mass. The overall dynamic equation of equilibrium for the structure-foundation-soil system during free vibration can be expressed in matrix notation as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=0 \qquad (1)$$

[K], [M], and [C] are the stiffness matrix, mass matrix, and damping matrix respectively of the whole system consisting of superstructure, footing, and supporting soil. $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acceleration, velocity, and displacement vectors relative to the soil base. The Eigenvalues and corresponding Eigenvectors are obtained using the mode superposition method.

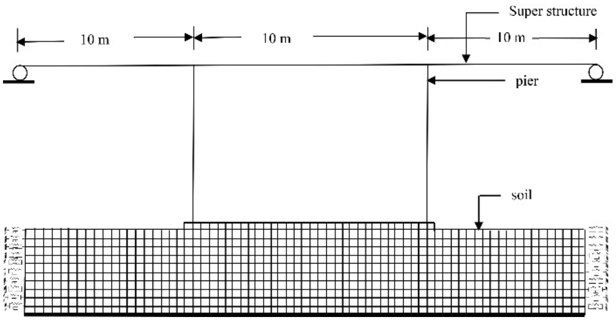

Fig.1. FEM discretization of bridge-foundation-soil system

2.2. FEM modeling of the continuous bridge to obtain the seismic response

In this part of the analysis, only the superstructure is considered for the analysis as shown in Figure 2. The deck slab and pier are modeled using two noded plane frame elements with three degrees of freedom at each node. The soil is not considered in FEM modeling and the base of the structure is fixed as if it is resting on a hard stratum. However, the geometric or material properties of the superstructure are chosen in such a way that the natural period of the structure is identical to the natural period of the structure resting on the soil as obtained from the first part of the analysis. This can be done by selecting the geometry of the pier or mass on the deck slab in such a way that the natural period of the fixed base structure is equal to the natural period of the structure on soil mass. The dynamic equation of equilibrium for the fixed base structure is given by the equation

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=F\{t\}$$

$\{F(t)\}$ is the nodal load vector due to earthquake ground motion and is given by the eq

$$\{F(t)\} = -[M]\{I\}\ddot{u}_g(t) \tag{2}$$

$\{I\}$ is the influence vector and $\ddot{u}_g(t)$ is the ground acceleration. The dynamic equation (2) is solved in the incremental form using Newmark's method to obtain the structure response at various time intervals during earthquake ground motion. The constant average acceleration scheme is used due to its unconditional stability. The fixed base structure response is similar to the structure response considering the footing and supporting soil in this study. Thus, this approach does not require modeling of the foundation and soil while obtaining a structure response at various time intervals.

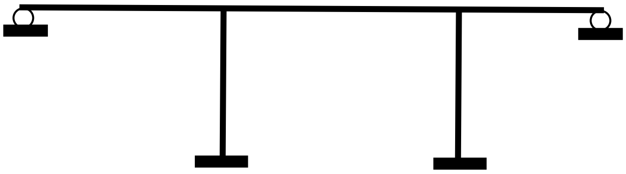

Fig. 2. Finite element discretization of bridge fixed at the base

3. NUMERICAL EXAMPLE

A three-span continuous bridge considered to demonstrate the simple approach proposed in this study is shown in Figure 3. Three types of soil such as soft (S1), medium (S2), and hard (S3) soils are being considered for the analysis. The material and geometric properties of the superstructure, pier, foundation, and supporting soil are as follows:

Superstructure:

span = 30.0 m

depth = 1.0 m

mass density = 2.50 kNsec^2/m^4

modulus of elasticity = 2.2x10^7 kN/m^2

Pier:

height = 8.0 m.

depth = 1.0 m.

mass density = 2.5 kNsec^2/m^4

modulus of elasticity = 2.2x10^7 kN/m^2

Foundation:

modulus of elasticity = 2.2x10^7 kN/m^2

mass density = 2.5 kNsec^2/m^4

Poisson's ratio = 0.15.

Soil:

modulus of elasticity for soft soil = 2000 kN/m^2

modulus of elasticity for medium soil = 6000 kN/m^2

modulus of elasticity for hard soil = 50000 kN/m^2

Poisons ratio = 0.33

mass density = 2.0 kNsec^2/m^4

The following four earthquakes are taken into consideration for the analysis with the SSI effect, to demonstrate the applicability of the proposed method for determining structure response

i. N-S component of EI Centro earthquake, 1940, peak acceleration 3.13 m/sec^2.

ii. Imperial Valley earthquake, 1979, peak acceleration, 4.28m/sec^2.

iii. Northridge earthquake,1994, peak acceleration, 8.26 m/sec^2.

iv. Chi–Chi earthquake at station TCU075, 1999, peak acceleration, 3.14 m/sec^2.

The EI Centro and Imperial Valley earthquakes have no long period characteristics and it is used in this study to represent the far-field (FF) earthquakes, whereas, the Northridge and Chi-Chi earthquakes were used to represent near-fault (NF) earthquakes. The time period, *T*, of the bridge on soft soil, medium soil, and hard soil obtained from the analysis as explained under section 2.1 is equal to 1.6, 1.025, and 0.71 sec respectively. Time period of the non-isolated bridge on a rigid base is equal to 0.67 sec. It can be observed that the time period for the bridge on hard soil is nearly equal to the time period of the bridge on a rigid base, whereas, for the bridge on soft and medium soils, it is more than that of the bridge on a rigid base. This indicates that the SSI makes the bridge on soft and medium soils more flexible compared to the bridge on a rigid base. To study the effects of the time period on the structure and to demonstrate the proposed approach, the peak acceleration and peak base shear response are obtained at various time periods of the bridge structure. Figure 3 shows the acceleration and base

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shear spectra for the bridge as a result of the analysis of fixed base structure without considering SSI (Figure 2) for the two FF (EI Centro and Imperial Valley) and two NF (Northridge and Chi-Chi) ground accelerations. The time period of the structure in the present study is varied by varying the stiffness of the bridge pier. The maximum ordinates of the spectral base shear and acceleration occur at the time periods of 0.24, 0.5, 0.4, and 0.3 sec respectively for the Northridge, EI Centro, Chi-Chi, and Imperial Valley earthquakes. In addition, it can be observed in Figure 3 that the bridge base shear and acceleration at the time periods 1.6 sec, 1.025 sec, and 0.71 sec are lesser than the base shear and acceleration of the bridge at the time period of 0.67 sec. These time periods are actually corresponding to the time periods of the bridge resting on soft soil (T=1.6 sec), medium soil (T=1.025 sec), and hard soil (T=0.71 sec). Hence, the above observations indicate that base shear and acceleration may decrease when the effect of SSI is considered in the analysis because responses at T=1.6 sec (corresponds to soft soil) and at T=1.025 sec (corresponds to medium soil) are lesser than the response of the bridge at T=0.67 sec (corresponds to structure on rigid base).

The actual base shear and acceleration of the bridge modeled by considering the structure, foundation, and soil (Figure 1) at various time intervals are also obtained for various earthquakes. The peak base shear and acceleration obtained from the analysis for soft (S1), medium (S2), and hard soils (S3) are tabulated in Table 1. The response of the non-isolated bridge is also shown in Table 1 for comparison. When the responses of rigid base structure at time periods 1.6 sec (soft soil), 1.025 (medium soil), and 0.71 (hard soil) shown in Figure 3 are compared with the responses from Table 1, it is interesting to observe that the response of the fixed base bridge (figure 2) with time period T=1.6 sec (corresponding to soft soil) is more or less similar to the actual response of the bridge on soft soil obtained from the SSI analysis (Figure 1). Similarly, the response of the fixed base bridge with a time period T=1.025 sec is also similar to the actual response of the bridge on medium soil with SSI obtained from the analysis.

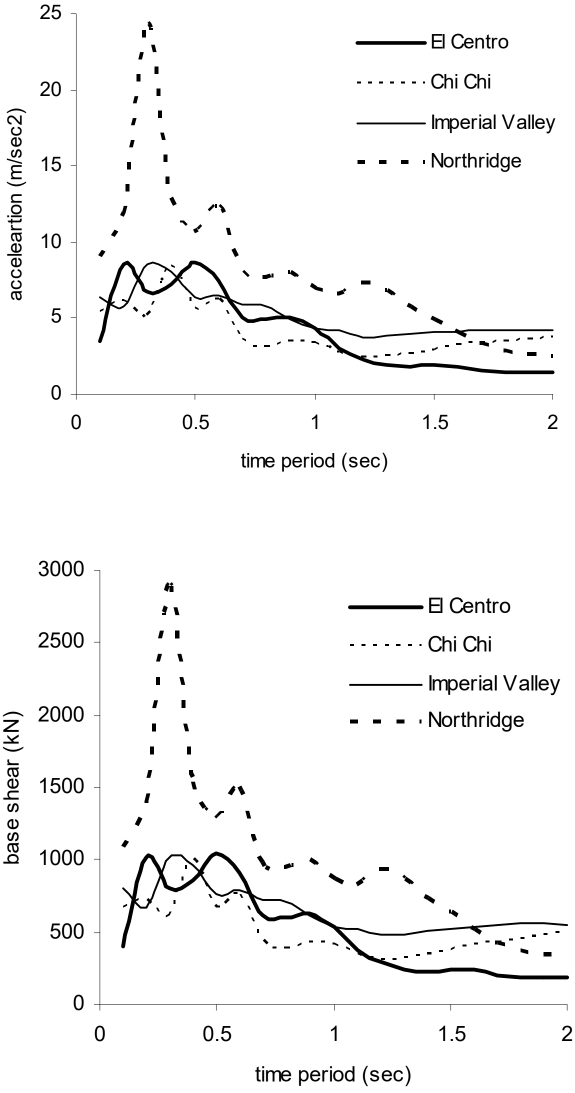

Fig. 3. Variation of response with the period for the bridge fixed at the base

The response of the fixed base bridge at time period T=0.71 sec (corresponding to hard soil) is also similar to the actual response of the bridge on hard soil obtained from the SSI effect analysis. These results clearly show that in order to obtain the structure response considering the SSI effect, it is not necessary to perform a time history analysis of the bridge using finite element modeling of the superstructure, foundation, and soil; instead, a similar response can be obtained by analyzing the bridge using only the superstructure fixed at the base. However, the time period of the fixed base bridge is to be similar to the time period of the bridge supported on soil mass.

Table 1 Peak base shear and acceleration for the bridge considering SSI

earthquake	response	rigid base	S1	S2	S3
Northridge	base shear (kN)	1092.23	483.22	679.04	931.03
	acceleration (m/sec^2)	8.94	3.95	5.61	7.62
Chi–Chi	base shear (kN)	454.37	415.59	343.39	420.67
	acceleration (m/sec^2)	3.75	3.52	2.93	3.45
El–Centro	base shear (kN)	698.15	313.33	464.84	584.85
	acceleration (m/sec^2)	5.75	2.58	3.83	4.79
Imperial Valley	base shear (kN)	739.55	425.28	474.69	713.81
	acceleration (m/sec^2)	6.09	3.44	3.93	5.84

4. SUMMARY AND CONCLUSIONS:

A simple approach to obtain the structure response considering SSI is proposed in this study. In this approach, if the time period of the structure considering SSI is known, then the response can be obtained from the analysis of only the superstructure fixed at the base. The applicability of the analysis is demonstrated through an example of a continuous bridge. The study found that the structure response when SSI is considered in the analysis is similar to the structure response when SSI is not considered, but the time period of the fixed base structure is to be similar to that of the structure when SSI is considered. This shows that if the time period of the structure with SSI is known, the structure response considering SSI can also be obtained from the analysis of fixed base structure.

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