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Study the Effect of Soil-Structure Interaction on Natural Period of Conventional Buildings Using Wolf's Cone Model

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ABSTRACT

Soil-structure interaction is often a difficult problem to study. This article uses Wolf's Cone Model and its application in the substructure method to investigate the effect of soil-structure interaction on natural period of conventional buildings. In accordance with Iran's Construction Code 2800, five soil types were considered. The studied structures were 4, 7, and 10 storey buildings. The following results were obtained: 1) The interaction between soil and structure was much more pronounced in finer soils, 2) The relative change in period was greater in shorter buildings, 3) The soil-structure interaction decreased as the ratio of "foundation dimension to soil thickness layer" increased.

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1. Introduction

There have been ongoing efforts for minimizing the destructive effects of earthquakes through proper seismic design of structures. In most cases, the foundation of a structure is assumed to be rigid. This is a correct assumption for hard or rocky ground, but not for elastic/flexible foundations where the interaction between soil and structure influences structural response. In Iran's Construction Code 2800, structural design is based on the applied forces and a rigid foundation is assumed for structures. As a result, deformations are produced in elastic foundation. Due to the difficult theoretical concepts and the complex methods involved in the soil-structure interaction, and that considering this interaction is both time-consuming and costly, simpler methods are needed in this regard; more practical methods which can be more tangible to engineers. Substructure methods greatly facilitate the implementation of analytical models. Wolf's Cone Model, a substructure method where soil is modeled by a series of springs and dampers, can be used as a proper substitute for the more complicated time-consuming methods [2].

Three evolutionary stages can be recognized for Wolf's Cone Method. In the first stage (1942-1974), a surface foundation resting on the surface of a homogeneous half-space was studied where waves propagated outward from a semi-infinite truncated cone [3,4]. In the second stage (1990-1994), the existing difficulties were removed

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through a reliable applied method which showed that reflected waves in a cone were the result of a material discontinuity [5, 6, 7, 8]. In the third stage (2001-2002), considerable simplifications were made by generalizing the above concepts (which were initially developed for one layer on one subspace) to a multi-layer subspace without any additional assumptions. This article aims to use Wolf's Model to determine structural frame periods by taking into account soil-structure interaction, and to study the way this interaction affects the equivalent static analysis of structures. The equivalent static analysis method, also used for conventional structures, is a popular method in Iran. In this method, the forces and deformations applied to the structure, are linear and based on the first mode of structural vibrations. Thus, using Wolf's Cone Method can be simplified and easily understood by engineers [9].

In modeling based on the substructure method, a substructure (the equivalent of a regular conventional structure) was represented by a mass and spring system. The spring stiffness value was calculated from the relations given in Iran's Construction Code 2800.

Wolf's Cone Method was used to model the soil substructure. The spring stiffness was obtained through trial and error on the basis of the combined soil-structure frequency. The one-degree-of-freedom system was used because all the calculations were based on the first mode of structural vibration. The elastic soil specifications were calculated using the ρ and Vs values given in Iran's Construction Code 2800.

2. Wolf's Equivalent Cone Methodd

In the cone model, soil is considered as a divergent cone and displacements are applied through massless foundations. The rules and relations applied in this method are based on geometrical cone relations as well as the beam theory in strength of materials. These relations are used for calculating the required values for spring stiffness and damping coefficient. The cone model consists of two main parts: In the first part, a semi-infinite environment is replaced with a semi-infinite truncated cone. As such environment does not actually exist in nature; the second part of the model addresses the problem of wave reflection and refraction at material discontinuities via forming secondary cones. Then, the primary cone and a proper number of secondary cones are duly combined to model the behavior of the actual environment [1].

2.1. The First Stage of Modeling: The Equivalent Cone

In this part of the model, a circular rigid massless foundation, called a disk, is assumed to be resting on a homogeneous subspace, and its translational (horizontal and vertical) and rotational (rocking and twisting) degrees of freedom are duly calculated.

In the one-dimensional strength of materials method, this dynamic system is modeled as a truncated semi-infinite bar with a vertical axis, the cross sectional area of which increases with depth. The reason for selecting a conical bar is that when a load is applied to a disk resting on the free surface of a subspace, stresses acting on the surface decrease with depth due to geometric scattering and this situation is best modeled with a cone.

According to the 3-D theory of elasticity, the aspect ratio Z/r is calculated by setting the static stiffness of the truncated semi-infinite cone equal to that of the disk resting on the subspace. Upon calculation of the aspect ratio, the opening angle of the cone (which is dependent on the Poisson ratio) can be obtained [1].

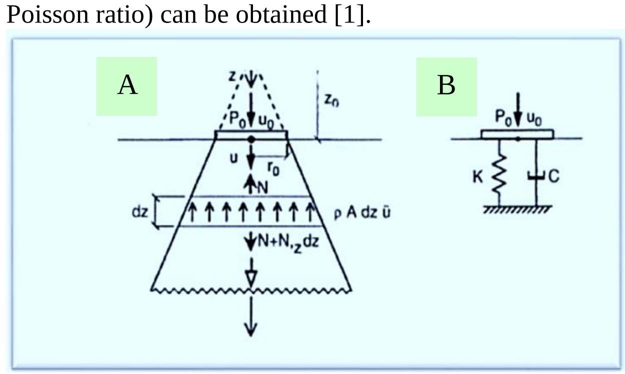

Figure 1. Translational degrees of freedom

2.2. The Second Stage of Modeling: The Secondary Cones

The second stage of calculations for a buried foundation involves wave mechanisms corresponding to the interface of layers where material discontinuities occur. As the incident wave propagating through the primary cone reaches the discontinuity, two waves are produced: a reflected wave and a refracted wave, each of which propagates through its respective cone. The reflected and refracted waves can then be expressed as functions of the incident wave by applying at the discontinuity interface the condition of consistency of displacements and the condition of equilibrium. The ratio of the reflected wave to the incident wave is called "reflection coefficient" which depends on the characteristics of the interface surface and the wave frequency [1].

3. Characteristics of the Models

3.1. Structural Modeling:

A structure vibrating in its first mode of vibration can be modeled by a one-degree-of-freedom system consisting of a lumped mass, a spring, and a damper. The values considered for mass and spring stiffness of the studied buildings are shown in Fig. 1 [2].

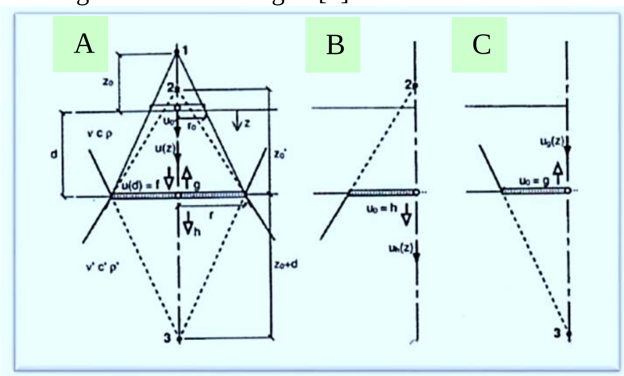

Figure2 . Wave propagation at a material discontinuity in a conical section: a) The incident wave producing the reflected and refracted waves; b) refracted wave behaving as a new incident wave; c) reflected wave behaving as a new incident wave

Table 1.
The specifications of the studied buildings

Period (s)	Stiffness (N/m)	Mass (kg)	No. of Storeys
0.555	1.169×10^8	912,000	4
0.796	9.092×10^7	1,459,200	7
1.013	7.719×10^7	2,006,400	10

3.2. Soil Modeling:

Due to the elastic behavior assumed for soil, Wolf's Cone Method was implemented for modeling it. Material damping and radiation damping are incorporated in the model via a damper parallel to the spring. Thus, the continuous environment represented by each soil layer can be modeled with a spring and a damper with frequency-dependent characteristics. Using CONAN, we obtained the spring and damper characteristics for the corresponding degree of freedom at various frequencies [2].

Examining the results showed that soil stiffness and damping were not very sensitive to frequency. Therefore, the stiffness and damping values for the two substructures (required for investigating soil-structure interaction) were assumed to be equal to those obtained at the natural frequency of the structure. As the results of this study were intended for usage inside Iran, the period of the structure and the soil characteristics (ρ and Vs) were duly determined from Iran's Construction Standard 2800. All the required parameters for Wolf's Model can be calculated from this information. Conventional buildings were represented by a 4-storey, a 7-storey, and a 10-storey building (Table 1). The 5 different grades of soil were also adopted from Code 2800 (Table 2). A 30-meter thickness was assumed for the soil layer. Beneath this layer, a semi-infinite layer with a shear wave propagation of 1500 m/s was considered.

The stiffness matrix, the damping matrix, and the mass matrix can be easily calculated by using basic equations of structural dynamics. Subsequently, the natural frequencies and periods of the combined system can be calculated. Structural analysis software can also be used for this purpose.

Table 2.
Soil characteristics based on Iran's Construction Standard 2800

Soil Type	Vs (m/s)	ρ (kg/m^3)
Type 1	800	2000
Type 2	500	2000
Type 3	300	2000
Type 4	200	1800
Type 5	100	1800

A glance on stiffness of springs and dampers which should be emulate effects of flexible soil, shows that the degrees of freedom which related to horizontal displacements are accompanied with some small stiffness and some grate damping ratios which seems completely different with rocking degree of freedom, where damping ratio often is about 6 percent and not affected by soil type and springs are generally stiffer than what found for horizontal movements.

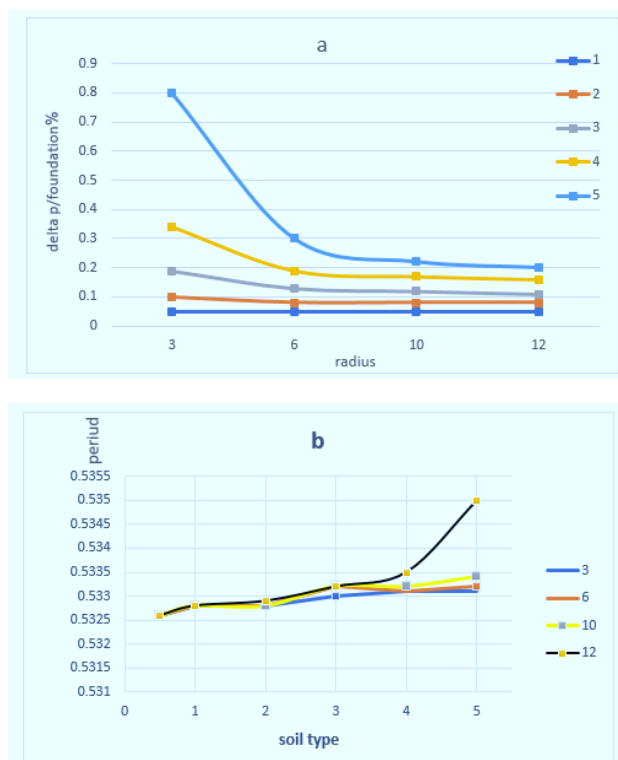

Figure 3. Soil-structure interaction for various soil types (a) and various foundation radii (b) in a 4-storey building.

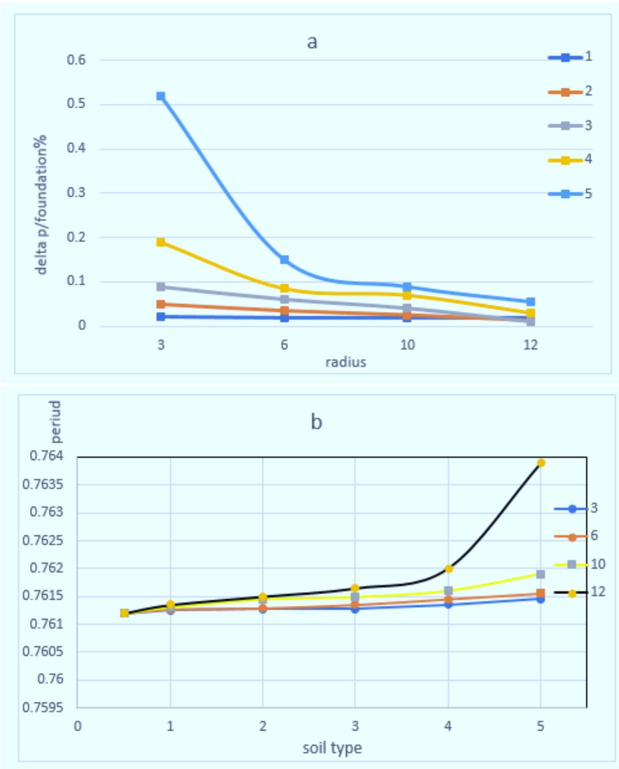

Figure 4. Soil-structure interaction for various soil types (a) and various foundation radii (b) in a 7-storey building.

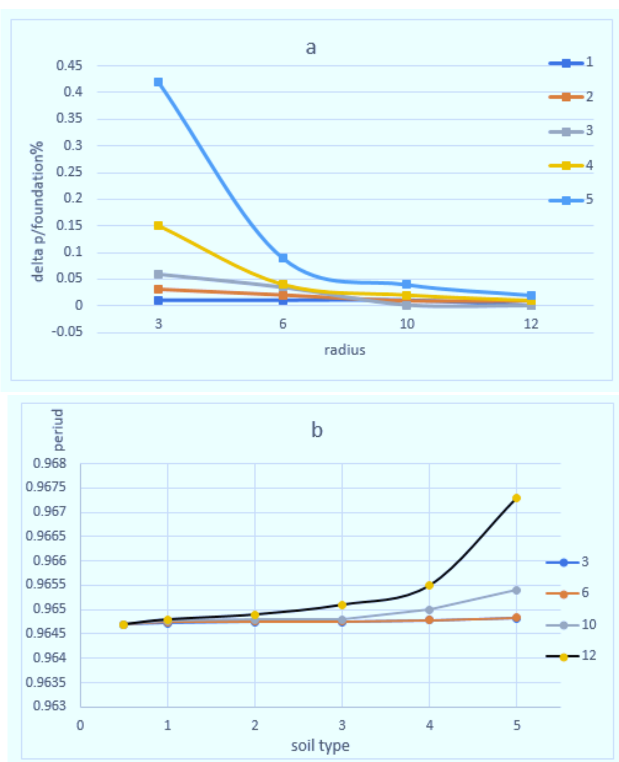

Figure 5. Soil-structure interaction for various soil types (a) and various foundation radii (b) in a 10-storey building.

4. Results and Discussion

The soil-structure interaction results obtained for the three representative buildings (4, 7, and 10 story) and four foundation radii (3, 6, 10, and 12 meters) are presented in Figs. 3 to 5. These results indicate the variations in structural period for different soil types as well as the period ratio variation with foundation radius.

5. Conclusion

1. Soil-structure interaction in finer soils (soil types 4 and 5) has a considerable effect on the natural period of the system.
2. As the number of stories (or period) of a building increase(s), the effect of soil-structure interaction decreases.
3. Wolf's Cone Method is a simple, efficient, and tangible method which is beneficial in engineering applications.
4. Increasing the ratio of foundation radius to soil layer thickness would decrease the effect of soil-structure interaction on the natural period of the structure.

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References

[1] Ehlers G. "The effect of soil flexibility on vibrating systems." Beton und Eisen 41.21/22 (1942): 197-203. (in German).

[2] Golmai SM. "Using Wolf's Cone Model to study the Effect of Soil-Structure Interaction on the Natural Period of Conventional Buildings." M.S. Thesis (2014).

[3] Meek JW, Veletsos AS. "A Simple Model for foundation in lateral and rocking motion." Proceedings of the 5th World Conference on Earthquake Engineering, IAEE, Rome, vol.2 (1974): 2610-2613.

[4] Meek JW, Wolf JP. "Insight on cutoff frequency for foundation on soil layer." Earthq Eng Struct Dyn 20 (1991): 651-665. (also in proceedings of the 9th European Conference on Earthquake)

[5] Meek JW, Wolf JP. "Cone Models for soil layer on rigid rock. II." J Geotech Eng Div, ASCE 118.5 (1992): 686-703. https://doi.org/10.1061/(ASCE)0733-9410(1992)118:5(686)

[6] Wolf JP, Meek JW. "Cone models for a soil layer on a flexible rock half-space." Earthq Eng Struct Dyn 22 (1993): 185-193. https://doi.org/10.1002/eqe.4290220302

[7] Wolf JP, Meek JW. "Rotational cone models for a soil layer on a flexible rock half-space." Earthq Eng Struct Dyn 23 (1994): 909-925. https://doi.org/10.1002/eqe.4290230807

[8] Wolf JP, Preisig M. "Dynamic stiffness of foundation embedded in layered half-space based on wave propagation in

cones." Earthq Eng Struct Dyn 32 (2003): 1075-1098. https://doi.org/10.1002/eqe.263

[9] Wolf JP, Jedix A. "Foundation Vibrations Analysis: The Strength of Materials Method." Translated by Mohaseb S., Tamsil Publications (2011).