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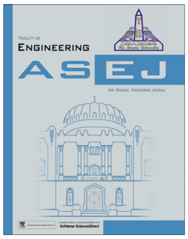

CIVIL ENGINEERING

Effect of piles on the seismic response of mosques minarets

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Abstract Minarets seismic behavior is not similar to other known structures, because of their unique characteristics such as slenderness, shape, and supporting system. This study is devoted to investigate pile foundation effects on minarets dynamic response. An advanced finite element models were employed to simulate this sophisticated problem. The analysis procedure is essentially 2-D model enhanced to satisfy the requirements of 3-D problems, using transmitting and viscous boundaries. Root mean square procedure is implemented to minimize the needed computer memory. The model has a main advantage of considering the full interaction between soil, foundation, and structure. Three artificial earthquakes' time histories were used as control motions at the bedrock surface.

Minaret (60.0-m height) was studied to investigate the effects of soil stiffness, pile length, diameter, and arrangement, on the minaret and pile dynamic behavior. Comparison between study results and conventional analysis method is illustrated. Study results, discussion, and conclusion are given.

1. Introduction

Mosque minarets are the most characteristic features of the Islamic architecture. Functionally, the minaret is an elevated structure intended for the Adhan crier as he summons people for prayer [1]. Recently, it became a tradition to attach a macerate to the religious construction. Along fourteen centuries, a lot of masonry minarets have been constructed in a variety of forms. Nowadays, the minarets are constructed from reinforced concrete that enabled both the architecture and the structural engineer to innovate and design high-rise minarets. One of the most important problems facing the structural designer is the dynamic response of such structure under lateral loads, especially under the effect of earthquake excitation.

The soil contact stress due to the heavy weight of these long minarets, over a relatively small area, may exceed the bearing capacity of the shallow soil layers. As a result, the choice of using pile foundation arises as one of the most convenient solutions. In addition, it has also a major role on structural stability (sliding and overturning stability), under lateral loads.

This study is devoted to investigate the effect of the pile foundation on the seismic response of the minarets structure. A wide range of dry sand formation (loose to very dense) is selected to simulate the upper sand formation. An extensive study has been carried out to investigate the effect of pile

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length, diameter, arrangement, and soil stiffness on the dynamic response of the minaret. Study has been extended to investigate factors affecting the fixation degree of the structure supports (foundation) and hence their impacts on the minaret fundamental periodic time (FPT) and the shear base. Moreover, the developed bending moment in the pile shaft is assigned to establish the effect of pile length and diameters. Sensitivity study is carried out to establish the optimum and economic design. Comprehensive comparison between numerical model results and conventional analysis method is illustrated. Study results, discussion, and conclusion are given.

2. Previous studies

Elwan [2] studied the response of historical masonry minarets. The study was directed toward the seismic analysis of the minaret of Al-Ghuri Mosque (46 m height), ancient Cairo, Egypt. A numerical model has been used using Drain-2DX code. Finally, a simple and robust method for the evaluation of the safety level of masonry minarets was suggested.

Chmielewski et al. [3] evaluated the natural frequencies and natural modes of 250 m high-multi-flue-industrial chimney, located in Opole power station, using finite element model and considering the flexibility of the soil. The analytical results were compared with experimental work using full-scale experimental investigation of the free vibration response. Study results established that soil flexibility under the chimney foundation has influence over natural modes and natural period.

Acar et al. [4] studied the seismic response of a reinforced concrete representative minarets located on the four different subsoil classes defined in the Turkish Earthquake Code (2007). Finite element was used considering the design spectra defined by the Turkish Earthquake Code. Analysis results showed that the dynamic response of the minarets changes significantly depending on the soil condition, where the maximum lateral displacement, in case of soft soil, was 80% larger than very rigid soil.

Dogangun et al. [5] investigated the dynamic behavior of historical unreinforced masonry minarets. Three representative minarets with 20, 25, and 30 m height were modeled and analyzed using two ground motions recorded during 1999 Kocaeli and Duzce, Turkey Earthquake. The modal analyses of the models showed that the structural periods and the overall structural response were influenced by minaret height and spectral characteristics of the input motion.

Sezen et al. [6] studied the probable cause of the extensive damage to reinforced concrete minerals (30 m height) by reviewing the observed failure modes and their seismic performance during 1999 Kocaeli and Duzce, Turkey Earthquake. Through dynamic analysis, the effects of spiral stairs, door opening, and balconies on dynamic behavior were examined.

Haciefend and Fahri [7] presented a stochastic seismic response analysis of masonry minarets subjected to random underground blast and Earthquake-induced ground motion, using three-dimensional finite element models. They conducted a parametric study to estimate the effects of the blast-induced ground motion on the stochastic response of the minaret. Three different soil types (soft, med. and firm soils) were considered. Study results showed that the underground blast and earthquake effects cause the stochastic behavior of minarets to change considerably.

Tabeshpour [8] carried out a nonlinear dynamic analysis of chimney-like towers. The significance of this study is mainly concentrated on model simplification that provides sufficient accuracy based on a nonlinear discrete model. Acceleration time histories scaled to different hazard levels were used as input excitation. Finally, it was found that the simplified model provided sufficient accuracy based on a nonlinear discrete model.

3. Methodology algorithm

Numerical simulation of the Dynamic-Soil–Structure Interaction (DSSI) problems is one of the most important challenges that facing the structural and geotechnical engineers. Recently, many investigators have been used the Finite Element Model (FEM) to simulate the complex mutual dynamic interaction between superstructure, substructure, and the underneath soil [3,4,7,9,10]. Although the finite element method became one of the most important and useful tools to simulate such sophisticated problem, the appropriate model should be carefully selected. In making such analysis, it is necessary to make sure that the boundaries of the finite element model are chosen sufficiently far from the structure, so that the full effects of radiation damping are correctly represented. Alternatively, the analytical model may be provided with transmitting boundaries, which absorb any wave effects emanating from the structure and thus simulate the effects of the extensive deposit [9–13]. Fig. 1a shows a schematic diagram for the used model, where it is shown that the model is basically 2-D model with some enhancement, using viscous boundaries to behave as a simplified 3-D model. As shown in Fig. 1a, the model is supported with viscous boundaries along the planar surfaces of soil slice of width (L). Accordingly, wave energy radiating along the axis of the slice will be absorbed by material damping, while energy radiating in directions normal to axis of the slice will be absorbed by viscous boundaries (3-D simulation of energy). Lysmer et al. [11] suggested taking (L) equals the structure width.

Based on the above-mentioned precautions and boundaries, an enhanced computational model, using Finite Element Method, has been used. The computational model consists of displacement-compatible quadrilateral elements (solid elements) to simulate the soil media and linear bending (frame) elements representing the structural elements. Using Ishibashi and Zhang Formulas (1993) [14], the nonlinear relation between shear strain and both shear modulus and damping ratio was implemented. The lower boundary of the model (bedrock) is assumed to be rigid and translates horizontally or vertically according to the used earthquake acceleration time history. Fig. 1b illustrates schematic diagram for a numerical model [11], showing the combination between solid elements, frame elements, and the bedrock rigid base.

4. Mathematical formulation

The equation of motion for a finite element representation of the system can be written:

$$[M]\{\ddot{x}\} + [K]\{x\} = -\{m\}a_b - \{V\} + \{F\} - \{T\} \qquad (1)$$

where $\{x\}$ are the displacements of the nodal points relative to the rigid base, $[M]$ and $[K]$ are the mass and stiffness matrices