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Finite element analysis of skirted foundation adjacent to sand slope under earthquake loading

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Abstract This paper reports the application of using a skirted foundation system to study the behavior of foundations with structural skirts adjacent to a sand slope and subjected to earthquake loading. The effect of the adopted skirts to safeguard foundation and slope from collapse is studied. The skirts effect on controlling horizontal soil movement and decreasing pore water pressure beneath foundations and beside the slopes during earthquake is investigated. This technique is investigated numerically using finite element analysis. A four story reinforced concrete building that rests on a raft foundation is idealized as a two-dimensional model with and without skirts. A two dimensional plain strain program PLAXIS, (dynamic version) is adopted. A series of models for the problem under investigation were run under different skirt depths and lactation from the slope crest. The effect of subgrade relative density and skirts thickness is also discussed. Nodal displacement and element strains were analyzed for the foundation with and without skirts and at different studied parameters. The research results showed a great effectiveness in increasing the overall stability of the slope and foundation. The confined soil footing system by such skirts reduced the foundation acceleration therefore it can be tended to damping element and relieved the transmitted disturbance to the adjacent slope. This technique can be considered as a good method to control the slope deformation and decrease the slope acceleration during earthquakes.

Introduction

There are many situations where footings are constructed on sloping surfaces or adjacent to a slope crest such as footings for bridge abutments on sloping embankments. When a footing is located on a sloping ground, the bearing capacity of the footing may be significantly reduced, depending on the location of the footing with respect to the slope. Therefore it may not be possible to use a shallow foundation and the use of uneconomic foundation types (piles or caissons) becomes the only appropriate solution of the problem. Therefore, over years, the subject of stabilizing earth slope has become one of the most interesting areas for scientific research and attracted a great deal of attention. Slope stability can be increased in different ways such as: modifying the slope surface geometry, using soil reinforcement, or installing continuous or discrete

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retaining structures such as walls, nailed elements or piles. There have been several studies on the use of slope reinforcement to improve the load bearing capacity of a footing on a slope [1–8]. These investigations have confirmed that not only that the slope stability can be increased but also both the ultimate bearing capacity and the settlement characteristics of the foundation can be significantly improved by the inclusion of reinforcements in either horizontal or vertical form (layers of geogrid, strips or geotextile) in the earth slope.

The problem of loaded slope with foundation was extensively investigated at a normal loading condition, static loading as presented in the above researches. However, a dynamic analysis of a loaded slope that is subjected to an earthquake loading cannot be thoroughly investigated, apart from a variety of researchers who studied only the behavior of slope under dynamic loading without considering existing structures adjacent to such slopes. The dynamic analysis of slopes were analyzed by many investigators [9–12]. Otherwise, the stability of seismically loaded slopes using limit analysis was studied [13,5].

These investigations are concerned with the analysis of slope shear failure as a whole, without identifying and analyzing the behaviors of the adjacent footing soil system. A conventional pseudo-static approach is still widely used in engineering designs of slope stability subjected to seismic loads. But this approach is generally not applicable to saturated soils with a high liquefaction potential, or to soils that will soften considerably when cycled. Accurate analysis of problems involving these soils requires elaborate dynamic finite element modeling with advanced constitutive relations capable of simulating the pore pressure generation during an earthquake, as well, to avoid the scale effect and the problem of shaking table. In the current research, full scale tests were used to simulate the actual skirted foundation and building behavior adjacent to a sand slope subjected to an earthquake using a finite element method by the commercial dynamic program PLAXIS version 8.2 [14]. This theoretical analysis helped in better understanding of the failure pattern and in discovering the results that cannot be measured in the laboratory for the adopted system.

Numerical modeling and selection of parameters

The plane strain model was used with the 6 node element. The mesh was generated by the program and refined in the area around the footing. The subsoil consisting of a deposit of a sandy layer of 20 m thickness and the slope height H, is constant and equal to 8 m. The slope angle is varied and taken 30°, 40° and 45°. The soil is assumed to be linear elastic in dynamic analysis. The material properties of the adopted sand to feed back the Mohr coulomb model (unit weight γ and corresponding modulus of elasticity E_{ref} were chosen according to the sand relative density which were studied at loose, medium and dense conditions, $\gamma = 15$, 17 and 18.5 kN/m^3). The mechanical characteristics of the tested subsoil were chosen according to main test results on sandy soils [15,16].

The Rayleigh damping is considered at vertical boundaries and taken as α, $\beta = 0.01$ in order to resist the Rayleigh waves. The plastic properties of soil (viscous properties) are defined by using material damping which was defined in Plaxis by Rayleigh (α and β), where a damping term is assumed which is proportional to the mass and stiffness of the system (Rayleigh damping) such that: $C = \alpha M + \beta M$, C is the damping coefficient, M is the mass, K is stiffness and α and β are Rayleigh coefficients. The Rayleigh damping is considered to be object-dependent in material data set to consider the plastic properties of soil during the dynamic analysis in Plaxis.

The ground water table is assumed at 2 m below the ground surface to consider the excess pore water pressure so the soil material is assumed to be undrained. The adopted building consists of 4 floors and a basement of 6 m in width as simulated in the program example PLAXIS [14]. The building and foundation are simulated as beam elements of elastic material. The floor and wall plate properties are (EA = 5 $\times 10^6$ kN/m, EI = 9000 kN/m/m with weight of 15 kN/m/m and Poisson's ratio $v = 0$). The building foundation is assumed as a reinforced concrete raft, it simulated as an elastic beam element, the raft thickness is 0.5 m thickness and its plate properties are EA = 105 kN/m and EI = 21.875 kN/m/m. The raft width (B) is taken as 6 m. The skirts are simulated as beam elements, elastic material. The steel skirts are adopted of variable thickness t (t = 4, 6 and 8 mm) and depth L (L = 0.5B, 1B, 1.5B and 2B). The skirts properties are axial stiffness EA and bending stiffness EI which were used to specify the skirts in the program.

The interface element was used between the soil and skirts plus foundation. The interface strength R_{inter} was taken 0.67, sand steel interfaces.

The earthquake is modeled by imposing a prescribed horizontal displacement at the bottom of boundary in contrast to standard unit length (Ux = −0.01 m and Uy = 0). Absorbent boundary conditions are applied at vertical boundaries to absorb the outgoing waves. The default setting to generate boundary calculations for earthquake loads is by using SMC files (strong Motion CD rom). Before the mesh generation, the water pressure can be activated to consider the pore water pressure to obtain the state of soil liquefaction. The parameters are varied to evaluate the following effects on the deformation characteristics of a slope (point 1, 2 and 3) and a point directly under the footing within the confined subgrade by such skirts. These parameters are; the ratio of the skirts depth to footing width (L/B), the ratio of the distance from the slope crest to the footing width (b/B), the slope angle (β), the soil relative density (Dr) and the skirts depth (t) The geometry of the finite element model adopted and problem notation for the analysis is shown in Fig. 1.

For the mesh generation, the global coarseness is set to coarse and the cluster inside the building is refined once. This is because of the high concentration of stresses that can be expected just in and under the building elements.

Analysis procedures

A series of dynamic numerical models were run at different studied parameters that were mentioned above; these parameters are skirts depth (L/B), distance from the slope crest (b/B), slope angle, subgrade density (γ) and skirt thickness (t).

The calculation procedure involves two phases. The first one is a normal plastic calculation in which the building is constructed. The second is a dynamic analysis in which the earthquake is simulated. In this phase the displacement is reset to zero and the time interval 10 s, the sub-step is set to 1. The