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Effect of soil reinforcement on rocking isolation potential of high-rise bridge foundations

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ABSTRACT

Based on recent studies, providing suitable conditions for a soil-structure system to behave non-elastically in response to the forced vibrations resulting from seismic activity is potentially advantageous. High-rise structures with rigid column-base connections often withstand considerable moments which can create plastic hinges at it. The Inclusion of rocking motions in the foundation in structural analysis is a new approach in seismic designs that can reduce the column-base moments and transfer the plastic hinge(s) to the soil. Creating soil slippage on failure surfaces, which in design concept is termed by "rocking isolation", can act as a "fuse" for protecting the superstructure against damages. Although favorable in terms of limiting the inertial forces applied to the superstructure, rocking motions can cause undesirable foundation settlement in structures with low safety factor against static vertical loads (F.S.v). Since the soil region yielded as a result of rocking motions lies in the shallow depths of the foundation, "shallow soil improvement" can be considered as an option to ensure that F.S.v is sufficiently large and to avoid unpredictable risks regarding residual rotation and increasing settlement. The geogrid and geocell were used as reinforcement elements at different depth ratios. Based on the results, using geocell at depth ratios less than 0.25 would reduce settlements effectively.

1. Introduction

In the past thirty years, scientific committees in seismic engineering have focused on studying methods for reducing structural failure caused by earthquakes the magnitudes of which exceed the limits predicted in the current structural design methods based on conventional construction standard and codes. Under such circumstances, the structure inevitably exhibits non-linear behavior. To maintain structural integrity in such cases, structures must be designed in such a way that the greatest failure potential can be allocated to the less significant points in the structure without the structure undergoing brittle failure.

The requirements in design standards allow inelastic behavior for the superstructure during strong earthquakes, as a result of which the seismic forces applied to the structure would decrease with increasing structural ductility. Under such conditions, designers generally neglect to take advantage of the already existing ductility at the soil-foundation interface. This stems from the fact that inspecting and repairing soil-foundation systems are sometimes relatively difficult and controversial. Therefore, future-oriented designers should ensure the safe performance of their soil-foundation system. To this end, different limits and criteria are considered. Under such conditions, mobilized load-bearing capacity, foundation uplift, slippage/sliding, or any combination of these factors is forbidden or strictly limited. This is done by considering conservative safety factors in designing the foundation against all the potential failure conditions. To avoid brittle failure in the structure as a whole, it is also necessary to impose strict ductility requirements on the superstructure.

In other words, an essential goal of traditional method in "foundation" design against seismic motions in the relevant codes is to avoid the full mobilization of "strength" in the foundation. In the words of EC8 (Part 2, Section 5.8), it is emphasized that:

> "…foundations shall not be used as sources of hysteretic energy dissipation, and therefore shall be designed to remain elastic under the design seismic action."

As a result, the geotechnical designer must ensure that the below-ground (and hence un-inspectable) support system will not even reach any kind of possible failure. In this conventional approach, "over-strength" factors plus factors of safety larger than 1 are introduced against each of feasible "failure" modes.

The experiences obtained from recent earthquakes confirm the fact that, in certain recorded seismic cases, the earthquakes were of such

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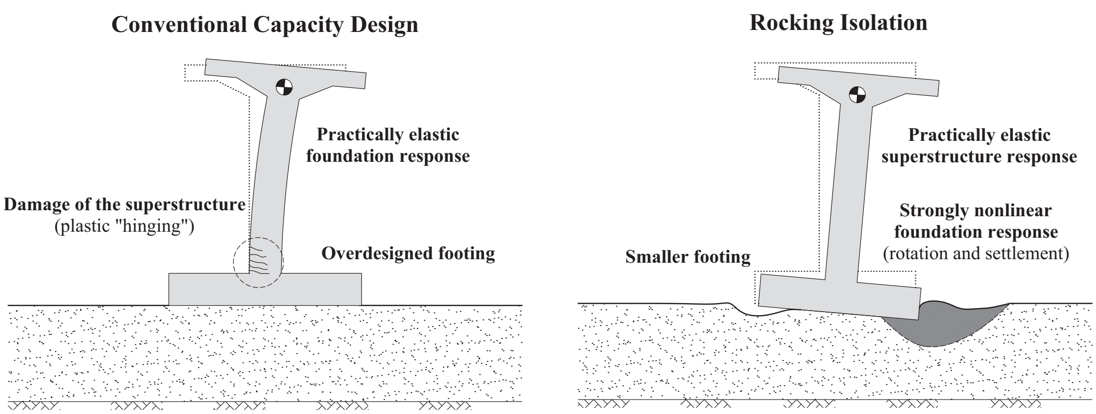

Fig. 1. Differences between structure and foundation behaviors in the traditional design as opposed to the design based on rocking isolation [30].

great magnitudes that the aforementioned measures failed to guarantee desirable and safe structural behavior during the earthquake in spite of observing all the seismic design safety criteria on the part of the relevant designers. Contrary to the common belief in design, previous studies [1–8] demonstrated that considering a non-linear soil-foundation system behavior can improve the general performance of the structure against different forms of failure and reduce the seismic acceleration transferred from the subgrade to the superstructure in several ways.

The non-linear soil-foundation-structure response is simulated by means of the following methods:

a) Winkler-based models that capture the settlement–rotation response of the footing [9–15].
b) Sophisticated macro-element models, where the entire soil-foundation system is replaced by a single element that describes the generalized force-displacement behavior of the foundation [16–19].
c) Finite elements (or finite differences), modeling the superstructure, the foundation, and the soil in detail [20,21].

Also the physical modeling has been developed to experimentally simulate non-linear soil-foundation–structure response, by means of the following models:

a) Large-scale dynamic and cyclic pushover testing, focusing on non-linear soil-foundation responses [22–24].
b) Centrifuge model testing, taking into account the non-linear superstructure responses [3,25–27].
c) Reduced-scale cyclic pushover and shaking table testing [28,29].

The idea of "rocking isolation" - where including soil failure in design acts as a fuse for the superstructure for preventing its failure - was introduced as a novel option in the seismic design of structures. As can be seen in Fig. 1 [30], given the cyclic and kinematic nature of the seismic shaking, the non-linear behavior of the foundation and its subgrade does not necessarily lead to failure. Furthermore, the non-linear behavior of the soil-foundation system can act as a fuse for reducing the energy transferred from the ground to the structure during the earthquake.

As the overturning moment applied to the foundation is the principal cause of the rocking motions, the probability of rocking motions (rotation of foundation) occurring in buried foundations and short structures is very low due to the foundation being restrained within the ground and the moment exerted on the foundation is small. Thus, rotation of foundation and the rocking isolation phenomenon must be evaluated in taller structures such as aerial tanks and bridge piers that often have a considerable foundation height to width ratio and a shallow foundation. In 2012, Drosos et al. [28] built a physical model of a bridge pier and deck under 1-g conditions on a shaking table to investigate how this phenomenon acted in such structures. Fig. 2 [28] shows the reduction of peak acceleration amplitude in a bridge deck as compared with that initially applied to the bridge subgrade, as well as the effect of the foundation size (dimensions) on this phenomenon.

A 1-DOF physical foundation-structure model (placed on a sand subgrade) was developed in this study to evaluate the non-linear response of the soil-foundation system which mainly caused by geometric non-linearity as well as the inelastic behavior of subgrade material such as slippage/slide and separation of the foundation from the ground. As previously mentioned, the study on the issue of rocking isolation in shallow foundations and how to control settlements have been the major concerns of many researchers in recent years. Since recent studies have focused on soil compaction and no literature has been found on effects of soil reinforcement effects on rocking isolation, in the present studies, the use of geogrid and geocell as a reinforcing element for soil has been considered. In this paper, the results of this improvement method have been compared with the soil compaction improvement method. Also, the present paper focuses more on controlling horizontal displacements of the foundation in the face of rocking movements, as an existing gap in the previous studies.

2. Rigid footings on flexible and rigid beds

If we place a structure with lumped mass m (at height H_{CM}) and foundation width B on a rigid subgrade and apply a horizontal load F to it at the level of its center of mass (Fig. 3), the structure begins to rotate at an angle φ around O upon the horizontal force F exceeding a certain threshold. Given the static balance equations governing the problem, the bending moment at the footing of the pier caused by the horizontal

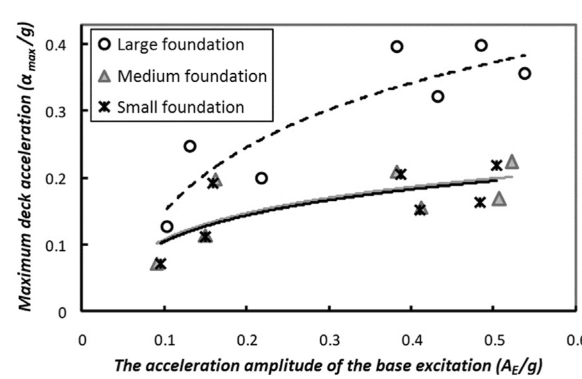

Fig. 2. The effect of rocking isolation on reducing the transfer of subgrade acceleration to the bridge deck in models having different foundation dimensions [28].