PhD Thesis

Development of a numerical algorithm for the dynamic elastoplastic analysis of geotechnical structures in two (2) and three (3) dimensions

by

Dimitrios K. Karamitros
Geotechnical Division, School of Civil Engineering, N.T.U.A.

Extended Abstract

An advanced numerical algorithm is developed, for the simulation of the monotonic, as well as the cyclic – dynamic response of non-cohesive soils, under variable cyclic shear strain amplitudes. The User-Defined Model (UDM) option was applied for this purpose, provided by the (commercial) Finite Difference codes FLAC and FLAC3d for the implementation of sophisticated constitutive models. The adopted constitutive model was the critical-state bounding-surface elasto-plastic model initially proposed by Papadimitriou et al (2001, 2002), as it was consequently modified by Andrianopoulos et al (2009, 2010).

Taking into account the three-dimensional nature of most geotechnical engineering applications, as well as the high computational cost associated with the performance of three-dimensional fully-coupled (effective stresses and groundwater flow) dynamic analyses, the algorithm that was developed with the programming language C++, was optimized, in order to minimize the required analysis time. This optimization process included the simplification of the iterative procedure for the application of the model's mapping rule (association of the current stress state to a conjugate point on the model's bounding surface), as well as the application of a computationally efficient "combined" explicit integration scheme, which may automatically switch between simple Euler integration and modified Euler integration with automatic error control and sub-stepping, depending on the local non-linearity of the stress-strain relationship.

The proposed numerical methodology was extensively verified, both in element level and in boundary-value problems. In element level, the algorithm was evaluated in terms of accuracy and computational efficiency, using iso-error maps, as well as through its application on various stress paths. Furthermore, the model was calibrated against a large number of laboratory tests, from the international literature. As far as boundary-value problems are concerned, the predictions of numerical analyses in both two (2) and three (3) dimensions were evaluated against the experimental results from a centrifuge test concerning the seismic performance of a shallow foundation in a liquefaction regime. Apart from the remarkable quantitative agreement which was observed during this one-to-one comparison, all trends observed during centrifuge and other large-scale experiments, regarding the liquefaction performance of shallow foundations, were also accurately predicted with the corresponding numerical analyses. Thus, the proposed algorithm was proved to be a valuable computational tool, that may be used not only for practical applications (i.e. to quantify the effects of liquefaction on geotechnical structures),

but also in research, to provide insight to complicated and highly non-linear dynamic interaction phenomena.

The above algorithm was consequently utilized, for the numerical investigation of a highly non-linear three dimensional problem of geotechnical earthquake engineering: the performance-based design of shallow foundations in a liquefaction regime. More specifically, strip (2-dimensional) and rectangular (3-dimensional) footings were considered, resting on a liquefiable sand layer, of varying thickness and relative density, underlying a non-liquefiable clay crust, with a varying thickness and shear strength. Furthermore, various sinusoidal excitations were examined (featuring varying applied acceleration amplitude, frequency and number of cycles), as well as strong motion records from recent earthquakes in Greece and abroad.

Based on more than 110 parametric analyses, simplified relations were consequently established, for the estimation of the (post-shaking) degraded bearing capacity, as well as the developing dynamic settlements. It should be definitely acknowledged that the proposed methodology was not the result of a "blind" statistical manipulation of the numerical data. On the contrary, it was based on the in-depth interpretation of the numerical results, and the adopted analytical expressions were carefully selected, so as to reflect the insight gained on the physical mechanisms governing foundation performance.

The accuracy of the analytical predictions was evaluated against field observations of liquefaction-induced damage, from three destructive earthquakes, namely the Niigata-Japan (1964), the Luzon-Philippines (1990) and the Kocaeli-Turkey (1999) earthquakes. The proposed methodology was also validated against experimental data, from well-documented centrifuge and large-scale shaking table tests.

Having verified the validity of the methodology's assumptions, the analytical relations were expressed in a non-dimensional form, in order to develop easy-to-use design charts, for practical applications. These charts allow the choice of appropriate footing dimensions and average bearing pressures, so as to fulfill the basic performance-based design requirements, in terms of an allowable post-shaking static factor of safety, as well as a statically and operationally acceptable value of dynamic settlements. Similarly, they may be used for the estimation of the required thickness and shear strength of a clay crust (or, in extension, the required depth for the application of soil improvement measures), in order to ensure the static and the operational capacity of the footing against subsoil liquefaction. Finally, the design charts indicate that a critical thickness of a non-liquefiable soil cap may exist, beyond which, subsoil liquefaction would not affect the bearing capacity of surface foundations, while the associated seismic settlements would be negligible.