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Nonlinear Behaviour of Laterally Loaded Long Piles Penetrating Soft Clay Below Water Table Subjected to Cyclic Loading—Sensitivity Analysis Part I: Theoretical Formulation

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ABSTRACT

This paper presents the theoretical formulation of sensitivity analysis of laterally loaded piles embedded in soft clay located below the water table. The pile structure is considered to be a 1-dimensional beam. The supporting soft clay is defined by means of a *p-y* model. The pile stiffness and material characteristics of a soil's *p-y* relationship are taken as the design variables. They are considered distributed parameters of a continuous type. The pile-soil system subjected to lateral loading is analyzed in the framework of sensitivity theory by means of an adjoint method for a nonlinear system. The first variation of functional of maximum deformations due to the changes of the design variables is formulated based on a virtual work principle with the aid of variational calculus. The unknown variations of generalized deformations imposed on the pile-soil system are determined by reference to physical relationships that are extended in the scope of sensitivity theory on the dependence on the design variables. The sensitivities of maximum generalized lateral deflections are determined in terms of sensitivity integrands associated with suitable variations of the design variables.

INTRODUCTION

The response of a pile to lateral forces and bending moments is a typical example of the soil-structure interaction system. The lateral loading can result from many sources, for instance, when the high-rise building is subjected to wind load, or when an earthquake induces waves that propagate in a lateral direction. Bridge abutments and supports are other examples of structures supported by piles that have to resist breaking forces exerted by moving vehicles. Offshore structures are the systems that support lateral load caused by ocean waves, water currents and various forces connected with operational processes (Reese and Van Impe, 2001). The laterally loaded long piles are considered a part of the infrastructure that contains assets in transportation, energy production, buildings and recreational facilities (Hudson et al., 1997).

The development of infrastructure systems integrates the design process with maintenance services, future rehabilitation, renovation and replacement activities in the overall planning and costing. Traditionally, infrastructure design practices have considered initial condition, load and material properties as the primary input variables for structural design without taking into account the effect of environmental and material degradation over time. Such an approach does not adequately assess the actual service life of the structure. The performance of an infrastructure element or facility is considered good if it performs as designed and provides an acceptable level of service over its intended life. The development of good performance models depends on the condition and assessment methods, load, material behaviour prediction and the taking into account of climatic and environmental conditions. It is important to identify key factors, in addition to usages that affect the performance of the structure in-service and its evaluation. The deterioration of the structure during in-service operations can be manifested by excessive deformations or various kinds of distress of strength types. The key factors that cause deterioration of the structure are load, material degradation, environment, construction quality and other mechanisms. The primary factor (Hudson et al., 1997) in most deteriorations of the deformation type is load and material aging. It is thus essential to develop a method that provides a theoretical basis for an assessment of maximum deformations expressed in terms of possible changes of material properties. It is particularly useful to refer such an analysis to the structural model that is employed in the design process, which defines an initial condition. The discussed criteria can be suitably introduced through the distributed parameter sensitivity theory. The application of sensitivity theory to the class of laterally loaded piles is useful because:

- it is developed in the vicinity of the initial solution considered during design of the structure;
- the material characteristics are considered spatial functions;
- it is able to indicate the locations of the changes of the system's material properties that are critical for an increase of maximum deformations;
- the performance functional of maximum generalized deformations that is formulated in the scope of variational calculus makes the analysis transparent with respect to spatial variables;
- it is possible to assess quantitatively the impact of each change of the material property on the change of maximum deformations.

The method of sensitivity analysis presented here is in reference to laterally loaded piles embedded in nonlinear soil and is based on the virtual work principle. Thus it contains intrinsically all the characteristic features this principle requires. It demands knowledge of the physical behavior of the entire system through the fact of involvement of the work of all internal forces of the entire system. This is mathematically expressed by means of a spatial integral. In the sensitivity formulation presented here, the

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KEY WORDS: Laterally loaded piles, nonlinear soil-structure interaction systems, infrastructure systems, distributed parameter sensitivity analysis of nonlinear systems, adjoint method, sensitivity operators/ sensitivity integrands.