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Parameters affecting laterally loaded piles in frozen soils by an efficient sensitivity analysis method

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ABSTRACT

In cold regions, accurately simulating the nonlinear responses of frozen soil–structure interaction (SSI) systems is of significant importance for the seismic safety assessment. This paper presents a finite element (FE) simulation of nonlinear lateral responses of a real reinforced-concrete filled steel pipe pile embedded in frozen ground at an outdoor test site in Fairbanks, Alaska. A pressure-independent multi-yield surface J_2 plasticity model is used to simulate the frozen soil behavior, while frame element with fiber section and nonlinear steel/concrete model are used for the pile. The FE analysis results agree well with the experiment results. Furthermore, the response sensitivities to various material parameters are computed by using an efficient and accurate gradient computation method, i.e., direct differentiation method (DDM), with limited additional computational cost. Based on DDM, the relative importance of material parameters on system responses is studied when the system is subjected to varying lateral deflections, respectively (corresponding to different levels of lateral loads such as earthquakes). Stiffness-related parameters are dominant when the system is subject to small deflections, while strength-related or post-yield parameters become dominant for large deflections. In addition, global responses are slightly more sensitive to material parameters of pile than the parameters of frozen soil. The response sensitivity to the unfrozen soil below the frozen ground crust is almost negligible. Finally, the response sensitivities to the soil parameters are observed to decrease when the distance of the soil from the pile increases. The sensitivity analysis methodology presented in this paper can be adapted to other frozen soil–pile interaction cases and the study results provide valuable insight for engineering practice.

1. Introduction

In Arctic and Sub-Arctic regions covered by thick seasonally frozen ground and permafrost, some structural damages during earthquakes have appeared to be directly attributed to the occurrence of frozen ground and ice formation. For example, recent researches in Alaska and Iowa have established clearly the significance of frozen ground effects on the seismic response of bridge foundations (Wotherspoon et al., 2010; Xiong and Yang, 2008; Xu et al., 2011; Yang et al., 2007, 2008). It is of great importance to assess the effects of the frozen soil on the seismic performance of superstructures (Sritharan et al., 2004; Suleiman et al., 2006). The mechanical properties of frozen soil depend not only on the temperature but also on water or ice content, loading rate, dry density, sample preparation method and soil type. Frozen soil has much higher stiffness and shear strength than unfrozen soil (Akili, 1971; Sayles and Haines, 1973; Stevens, 1973; Vinson et al., 1983a), which greatly affects the characteristics of soil–structure interaction (SSI) behavior of the system.

For the complex nature of frozen soil and SSI effects, the response sensitivity study with respect to various model parameters are important for gaining insight into the SSI systems involving frozen soils and for performing necessary complementary study (Conte et al., 2003; Kleiber et al., 1997). Furthermore, the response sensitivity analysis in the context of finite element (FE) method represents an essential component for gradient-based optimization methods needed in various subfields of structural and geotechnical engineering such as structural reliability analysis, structural/geotechnical system identification, and FE model updating (Ditlevsen and Madsen, 1996; Kleiber et al., 1997). In addition, FE response sensitivities are invaluable for gaining insight into the effect and relative importance of system and loading parameters in regards to structural response behavior.

Several methods are available for response sensitivity analysis, such as the finite difference method (FDM), the adjoint method (AM), the perturbation method (PM), and the direct differentiation method (DDM) (Conte et al., 2003, 2004; Gu and Wang, 2013; Gu et al., 2009a; Kleiber et al., 1997; Zhang and Der Kiureghian, 1993). FDM is the simplest method for response sensitivity computation, but is computationally expensive and can be negatively affected by numerical noise (i.e., truncation and round-off errors). AM is extremely efficient

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for linear and non-linear elastic systems, but is not a competitive method for path-dependent problems. PM is computationally efficient, but generally not very accurate. DDM, on the other hand, is very general, accurate and efficient and is applicable to any material constitutive model including both path-independent and path-dependent models. The computation of FE response sensitivities to system and loading parameters based on the DDM requires extension of the FE algorithms for response-only computation (Conte et al., 2003; Gu et al., 2009a; Gu and Wang, 2013).

This paper introduces the DDM-based response sensitivity analysis method as a new approach for efficient and accurate response sensitivity analysis of frozen soil–structure interaction systems subject to lateral load. The sensitivity analysis results provide an assessment of relative importance of various material parameters for selected global and local responses of the system. The local responses represent the responses belong to the section/material level in the FE hierarchies, such as the moment/curvature in a gauss point of a frame element of the pile (also called section), the stress/strain at a Gauss point of a soil element. Based on the response sensitivity analysis results, the following problems are studied in details: (1) parameter importance rankings (IRs) when the system is subjected to small and large lateral loads; (2) comparison of relative importance between the material parameters in reinforce concrete pile, frozen soil and unfrozen soil; and (3) response sensitivities with respect to the parameters of soil at increasing distance from the pile.

The organization of this paper is as follows: Section 2 presents numerical simulation method based on nonlinear finite element method (FEM) of a frozen soil–pile system, including a frozen soil model (Section 2.1), a pile model (Section 2.2) and soil–pile connection and boundary conditions (Section 2.3); Section 3 describes response sensitivity analysis based on the direct differentiation method (DDM), including the general DDM framework (Section 3.1) and an extension of DDM to frozen soil–pile systems (Section 3.2); Section 4 discusses the application of the above response and response sensitivity analysis methodologies to a field experiment, including an introduction of the experiment and a finite element (FE) model (Sections 4.1 and 4.2), response analysis (Section 4.3), verification of the DDM-based response sensitivity analysis (Section 4.4) and sensitivity analysis results (Section 4.5). Section 5 presents several conclusions.

2. Nonlinear finite element (FE) model of a frozen soil–pile system

2.1. Multi-yield surface material model for frozen soil

The frozen soil is modeled by a pressure-independent multi-yield surface J_2 plasticity material model (as shown in Fig. 1), which was developed and applied to soil mechanics by Prevost (1977, 1978a). The model was further developed by Elgamal and co-workers by introducing a new hardening rule to improve its numerical stability and increase its practical applicability (Elgamal and Gunturi, 1993; Elgamal et al., 1996; Yang, 2000; Yang et al., 2003). Recently, the model was implemented in OpenSees and has seen increasing usage for modeling soil or soil–structure interaction problems (Elgamal et al., 2008; Zhang et al., 2008). OpenSees is an open source software framework for advanced modeling and analysis of structural and geotechnical systems (Mazzoni et al., 2006). In contrast to the classical J_2 plasticity model with a single yield surface, the multi-yield surface J_2 plasticity model employs the concept of a field of plastic moduli to achieve a more realistic representation of the material plastic behavior under cyclic loading conditions. This field is defined by a collection of nested yield surfaces with each yield surface maintaining constant size in the stress space. At each time step, it is not possible to know a priori which and how many yield surfaces will be reached until global equilibrium is achieved at the end of the step. The nonlinear shear behavior of soil materials is characterized by an experiment-based smooth shear stress–strain backbone curve, which is replaced by a piecewise linear approximation in the numerical algorithm. An associative flow rule is used to compute the plastic strain increments. A pure deviatoric kinematic hardening rule is employed to conveniently generate hysteretic cyclic responses (Yang, 2000; Yang et al., 2003). Frozen soil mechanical properties such as shear strength parameters and stiffness parameters are not sensitive to confining pressure, particularly in low pressure cases (Baker et al., 1982; Vinson et al., 1983b). Therefore this paper uses a multi-yield surface J_2 plasticity model to simulate the stress–strain behavior of frozen silty soils.

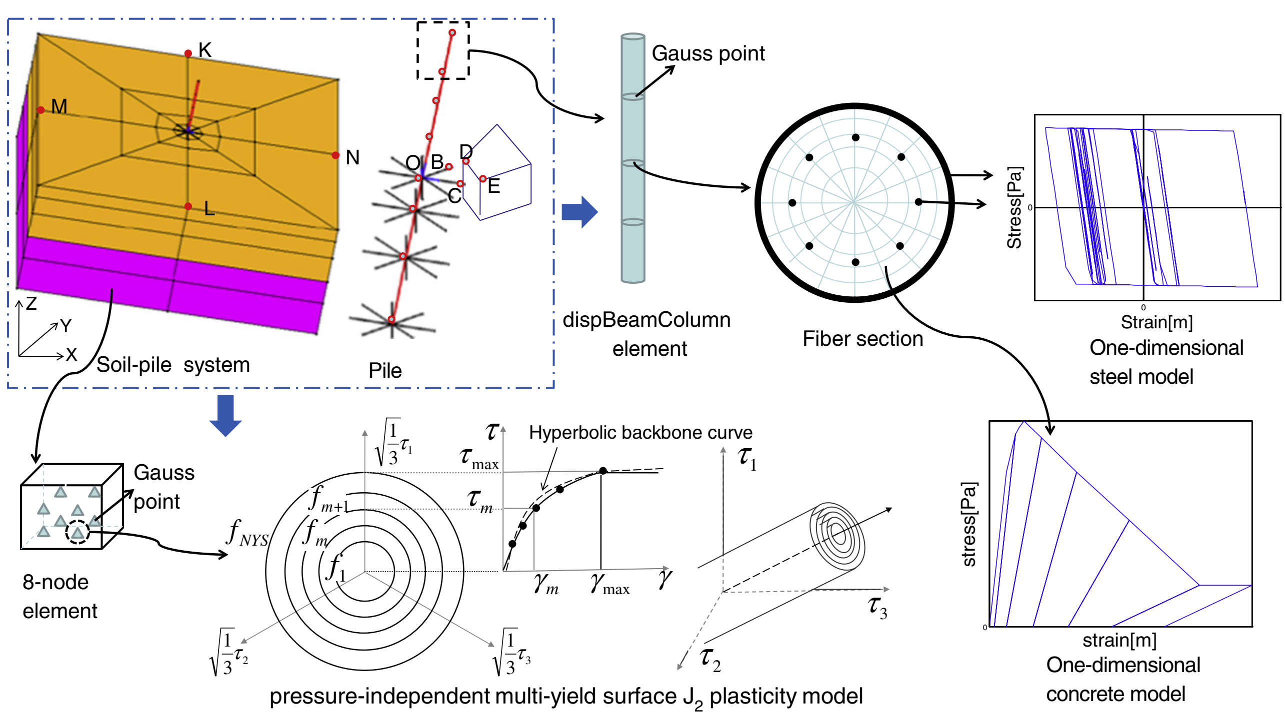

Fig. 1. Nonlinear finite element (FE) model of a frozen soil–pile system.