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'Skipped cycles' method for studying cyclic loading and soil–structure interface

S. Burlon [a], H. Mroueh [b,*], J.P. Cao [b]

[a] Université Paris-Est, IFSTTAR, Paris, France
[b] Laboratory of Civil Engineering and Geo-environment of Nord, Lille, France

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ABSTRACT

This paper deals with a numerical calculation method related to the modelling of soil–structure interfaces subjected to a large number of cyclic loadings. The first part of the paper focuses on the presentation of a 'skipped cycles' method to reduce time computation without influencing the calculation precision of strains and stresses. This method is based on an extrapolation of the plastic strains calculated during the previous loading cycles. The second part of the paper presents the numerical validation of the 'skipped cycles' method. A constitutive model for soil–structure interfaces subjected to cyclic and transient loads is briefly presented. The capabilities of this model to take into account cyclic phenomena like softening or hardening and shakedown or ratcheting are illustrated by several academic examples. The performance of the 'skipped cycles' method is then studied through two examples including, on the one hand, a shearing resistance test with four interface elements, and on the other hand, an axially loaded pile with sixty interface elements. The results are compared with those obtained by means of a classical 'step by step' method and show that the 'skipped cycles' method provides significant reduction in terms of time computation without lowering the numerical calculation precision.

0. Introduction

Cyclic behaviour of soils and soil–structure interfaces is of major importance for the reliability of many structures such as off-shore structures, wind power plants or vibrating machines. Indeed, waves, wind or vibrations impose transient and cyclic actions to these structures, which may induce too large displacements and lead to a loss of stability. In order to design these structures subjected to such actions and particularly to calculate the accumulated strains and displacements, reliable methods including relevant cyclic constitutive laws for soils and interfaces are required. At present, this type of calculation is possible and can be easily addressed by the finite element method or the finite difference method.

Nevertheless, the use of these numerical methods for large number of cycles (>500) with classical incremental resolution scheme ('step-by-step' method) leads to some costly calculations in terms of computational time. Furthermore, this type of iterative methods may induce some important numerical cumulative errors as underlined by Niemunis et al. [8].

Alternative methods can be performed to overcome these numerical drawbacks. Inspired from the resolution of complex mechanical problems for structures subjected to fatigue and creep effects, a first approach, known as the rapid cycling creep method, is proposed by Ponter and Brown [12–14] and completed by Spiliopoulos [18]. It is assumed that the total stress can be split into two parts: a cyclic elastic stress and a self-equilibrating stress caused by the nonlinearity of the constitutive model. Several authors propose alternative approaches derived from this first method. Kodaissi et al. [10] present a method based on the homogenisation of the loading history. This approach is nevertheless limited to the cases where the cyclic loading period does not tend to zero. The method developed by Sai [15] for metal alloys subjected to high temperature is based on the extrapolation of internal variables from a Taylor expansion. In the framework of the finite element method, Shahrour and Meimon [16] also use a homogenisation method to estimate the evolution of plastic strains at each integration point of the mesh by considering the stress range of the previous loading cycles. Recently, Niemunis et al. [8] and Wichtmann et al. [19], Wichtmann et al. [20] propose a high cycle accumulation model to predict the strain variations during the loading cycles without estimating the cyclic stress variation. This model is based on a large number of parameters derived from an

* Corresponding author. Tel.: +33 320434566.
E-mail address: hussein.mroueh@polytech-lille.fr (H. Mroueh).

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extensive amount of laboratory tests. Achmus et al. [1] suggest a method based on the definition of a secant modulus taking into account the degradation stiffness of the soil. Currently, Papon et al. [11] develop an application of the time homogenisation method for simulating undrained triaxial and pressuremeter tests for normally consolidated clays. Their results show that the kinematic variables of the constitutive models have a major influence on the numerical procedure of the method and may lead to some impaired performances. They conclude on the necessity to develop in the same time both constitutive models and numerical strategies.

In order to simulate the behaviour of a structure subjected to high number of cyclic loadings, this paper present a numerical strategy called here the 'skipped cycles' method. Inspired from a method developed by Sai [15], it aims to reduce calculation time without lowering the numerical scheme quality and without influencing the calculation precision of strains and stresses. Nevertheless, this method still needs the use of constitutive laws accounting for cyclic effects. The first part of the paper gives an overview of the 'skipped cycles' method, which is only based on an extrapolation of the plastic strains calculated during the previous loading cycles. An extension of the method is proposed for the cases where the plastic strain evolution is nearly constant. In a second part, in order to numerically compare the 'skipped cycles' method and a 'step-by-step' method and to address geotechnical problems where cyclic effects are an important issue, a constitutive model for soil–structure interfaces subjected to cyclic and transient loads is briefly presented. The capabilities of this model to take into account cyclic phenomena like softening or hardening and shakedown or ratcheting are illustrated by several academic examples. Then, the performance of the 'skipped cycles' method is studied through two examples including, on the one hand, the repeated cyclic shearing of two soil volumes separated by an interface with four elements, and on the other hand, an axially loaded pile with sixty interface elements. In each case, the 'skipped cycles' method efficiency is compared to a 'step-by-step' method by considering the time computation and the numerical cumulative errors in terms of displacements or stresses.

1. 'Skipped cycles' method

1.1. Principles

Let Ω designate a soil volume subjected to repeated cyclic periodic forces F on the boundary Γ_f and zero prescribed displacement on the boundary Γ_u. The resolution of this problem addresses the calculation of the evolution of both strain and stress tensors between two any cycles i and j. These two cycles are characterised by two identical loading levels ($F(i) = F(j)$). In this framework, the concept of the 'skipped cycles' aims to calculate the structure behaviour between these two cycles i and j without calculating the response of the system for each intermediate cycle (which can be obtained by a conventional 'step-by-step' method). The calculation from the cycle i to the cycle j is based on the extrapolation of internal variables (kinematic and isotropic hardening variable tensors) by means of a Taylor expansion. For this type of calculation, the main issue concerns the internal variable evolution that is different for each integration point although the cyclic loading applied is periodic.

In this paper, the numerical technique used is only based on the extrapolation of the plastic strain tensor. Due to cyclic effects, between two cycles i and j, for each integration point, accumulated plastic strains $\Delta\varepsilon_{ij}^p = \varepsilon_{ij}^p(j) - \varepsilon_{ij}^p(i)$ are generated even for the same loading level (Fig. 1). The problem is then governed by the following equations:

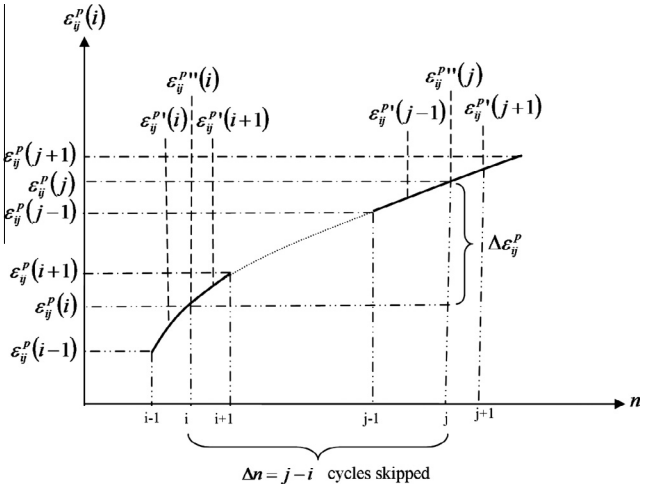

Fig. 1. Relationship between cumulative plastic strain at cycle i and $j = i + \Delta n$.

– At the cycle i, the balance equation is the following:

$$div\sigma_{ij} + F_i = 0 \text{ on } \Omega \tag{1a}$$

$$\sigma_{ij}n_j = T_i^f \text{ on } \Gamma_f \text{ and } u_i = 0 \text{ on } \Gamma_u \tag{1b and 1c}$$

– At the cycle j, the balance equation is the following:

$$div(\sigma_{ij} + \Delta\sigma_{ij}) + F_i = 0 \text{ on } \Omega \tag{2a}$$

$$\Delta\sigma_{ij}n_j = 0 \text{ on } \Gamma_f \text{ and } u_i = 0 \text{ on } \Gamma_u \tag{2b and 2c}$$

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^e + \Delta\varepsilon_{ij}^p \text{ and } \Delta\sigma_{ij} = \mathbf{C}\Delta\varepsilon_{ij}^e \tag{3a and 3b}$$

where σ_{ij} is the stress tensor at the cycle i, $\Delta\sigma_{ij}$ is variation of the stress tensor between the cycles i and j, F_i are the volumetric forces, u_i the displacement field, $\Delta\varepsilon_{ij}$ is variation of the strain tensor between the cycles i and j, $\mathbf{C}$ is the stiffness tensor, the upper indexes e and p respectively refer to the elastic and plastic strains and n_j denotes the outward normal unity vector to Γ_f.

Considering a virtual displacement field v_i, the variational formulation of the local problem defined by the balance equation leads to the following equations:

$$\int_\Omega v_i div(\sigma_{ij} + \Delta\sigma_{ij})d\Omega + \int_\Omega v_i F_i d\Omega = 0 \tag{4a}$$

$$\int_\Omega v_i div\Delta\sigma_{ij}d\Omega = 0 \text{ since } \int_\Omega v_i div(\sigma_{ij})d\Omega + \int_\Omega v_i F_i d\Omega = 0 \tag{4b}$$

By using an integration by parts, we obtain:

$$-\int_\Omega grad\, v_i(\Delta\sigma_{ij})d\Omega + \int_{\Gamma_f} v_i\Delta\sigma_{ij}d\Gamma_f = 0 \tag{4c}$$

According to Eq. (2a), we obtain:

$$\int_\Omega grad\, v_i(\Delta\sigma_{ij})d\Omega = 0 \tag{4d}$$

$$\int_\Omega grad\, v_i(\mathbf{C}\Delta\varepsilon_{ij}^e)d\Omega = 0 \tag{4e}$$

$$\int_\Omega grad\, v_i(\mathbf{C}\Delta\varepsilon_{ij})d\Omega = \int_\Omega grad\, v_i(\mathbf{C}\Delta\varepsilon_{ij}^p)d\Omega \tag{4f}$$

The term $\int_\Omega grad\, v_i(\mathbf{C}\Delta\varepsilon_{ij}^p)d\Omega$ corresponds to the nodal forces that are to apply to the system to reach the cycle j from the cycle i. In the