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An energy method for deformation behavior of soft clay under cyclic loads based on dynamic response analysis

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ABSTRACT

Soft clay is fragile to be disturbed and to produce deformation under cyclic loads. A simple theoretical energy method is presented to explore the dynamic response of soft clay under cyclic loads, then to discuss its deformation behavior. In the formulation, equations are derived based on general thermodynamic principle and Newton's laws of motion. A series of cyclic triaxial tests are conducted for undisturbed samples of soft clay to verify the proposed method. Cumulative deformation is computed by the proposed approach. Results are compared with the experimental data, and good agreement is achieved. This paper develops a new insight to describe deformation behavior of soft soil under cyclic loads, and to predict the plastic accumulative deformation.

1. Introduction

Plastic deformation for soft soils can be produced under cyclic loads caused by traffic vehicles, waves, operation of machinery, etc. [1–6]. This deformation could be accumulated over time, and will bring high maintained costs and reduced design life. Taking Shanghai Metro Line 1 for example, tunnel settlement was relatively small (2–6 mm) during the first two years before formal operation (formal operation at 1995), but then increases year by year, reaching 60 mm in 1997, 150 mm in 1999, and up to 280 mm in 2007 [7]. Therefore, knowledge of cumulative plastic deformation and prediction methods for soft soil under cyclic loads are essential for design and maintenance cost control.

Deformation behavior of soft soils under cyclic loads has been investigated by many researchers. The existing methods can be mainly classified into two categories: theoretical method and experimental/empirical method. Generally, the theoretical method is firstly based on certain constitutive models of soils, such as, yield surface model [8,9], bounding surface model [10–14], and visco-elastic–plastic model [15,16]. Then deformation of each cycle can be computed by the constitutive models. The second method is empirical model, which is based on laboratory experimental or in-site tests, to predict accumulative plastic deformation by considering various influencing factors such as soil type, soil properties and, stress state. Among numerous empirical models, one of the most often used is a power model, which is first proposed by Monismith et al. [17] and then modified by Li and Selig [18], Chai and Miura [2], Huang et al. [19]. In addition, some other empirical models or semi-empirical models have been developed [3,4,20–26]. Compared with the theoretical method, the empirical method has become more and more popular in recent years because of its simplicity and satisfactory performance in practical engineering applications. However, the theoretical method is a fundamental and absolutely necessary tool for further exploring and understanding deformation mechanism. Therefore, this paper tries to provide a simple theoretical method in terms of energy to investigate the plastic accumulative deformation of soils under cyclic loads.

The aim of this paper is to present a theoretical method based on single freedom vibration equation, and to estimate the accumulated plastic deformation of soft clay subjected to cyclic loads. Since movement and deformation of the object is always accompanied by energy changes, therefore, it is possible to use the energy change to describe dynamic response and deformation behavior of soft soil under cyclic loads. The rest of this paper is organized as follows. We employ laws of thermodynamics in combination with vibration differential equation of soil to carry out a rigorous formula derivation for calculating plastic strain accumulation energy under cyclic loads. Then, a number of cyclic triaxial tests are conducted, and comparison between the tested results and computed results is made to verify the proposed model. Limitations of the proposed model were discussed in the last part of the paper.

2. Methodology

2.1. Literature review of energy method in this field

Compared with the existing theoretical (constitutive models) and

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empirical methods (such as the power model proposed by Monismith et al. [17] and its improved models) reviewed in the above, the energy approach has several advantages such as its independence of the load waveform and the type of testing device [27]. The most important among them is that energy is a scalar, which determines its quantity can be directly superimposed without the need to consider its direction. This advantage makes a much simpler for solving complex issues by use of energy approach.

The study on the soil vibration problem using energy method began from Nemat-Nasser and Shokooh [28]. Based on the idea of energy dissipation, they studied the densification and liquefaction of cohesionless soils under vibration loads by analysis of the relationship between excess pore water pressure and dissipated energy in the process of vibration. Following the study by Nemat-Nasser and Shokooh [28], an energy-based liquefaction evaluation method (EBM) was proposed by Davis and Berrill [29] and applied in liquefaction assessment by several other researchers [30–39]. Azeiteiro et al. [40] carried out study on energy dissipated in undrained cyclic triaxial tests, and investigated the correlation between the energy dissipated per unit volume and the generated excess pore water pressure. In addition, some researchers study response of soil deposits and of structures with using formulation of the solutions in terms of energy carried by seismic waves [41–43]. Nevertheless, most of the existing literatures for energy approach focus on sand liquefaction, very rare on dynamic response and cumulative plastic deformation saturated soft clay.

2.2. Theoretical derivations

It could be learned from the laws of thermodynamics and conservation of energy that energy may neither be created nor destroyed and the sum of all the energies in the system is a constant. Therefore, the total mechanical energy produced by external cyclic loads is equal to the sum of dissipated energy generated by damping of system, kinetic energy, elastic potential energy and plastic deformation accumulation energy, that is:

$$W_F = W_f + E_k + E_e + E_P \tag{1}$$

where, W_F is the total mechanical energy produced by external cyclic loads in the loading process of system; W_f is dissipated energy generated by damping; E_k is kinetic energy of system obtained at the time of calculating; E_e is elastic potential energy of system obtained at the time of calculating; E_P is plastic accumulative deformation energy during the cyclic loading.

Since the cyclic loads adopted in the most of cyclic triaxial tests are harmonic loads, we choose sinusoidal harmonic load as the external excitation load F expressed as follows.

$$F = F_0 + F_A \sin \omega t \tag{2}$$

where, F_O is a base value of cyclic loads [N]; F_A is dynamic amplitude of loads [N], and its value is smaller than the base value in order to avoid tensile stress, namely $F_A < F_0$; ω is circular frequency [s^{-1}], and $\omega = 2\pi/T$, in which T is cycle time [s]. Since the external excitation force (the applied cyclic loads) F always exist in the whole loading process, the total mechanical energy W_F is the product of the force and displacement z of the object s on which the force acting. The object displacement z is a function of object velocity v and acting time t. Thus, the W_F can be expressed as follows.

$$W_F = Fz = F\int_0^t vdt = \int_0^t (F_0 + F_A \sin \omega t)vdt \tag{3}$$

In which, v is the velocity of object on which the force acting on[m/s]; t is the time [s].

Similarly, the dissipated energy W_f caused by damping f can be expressed as

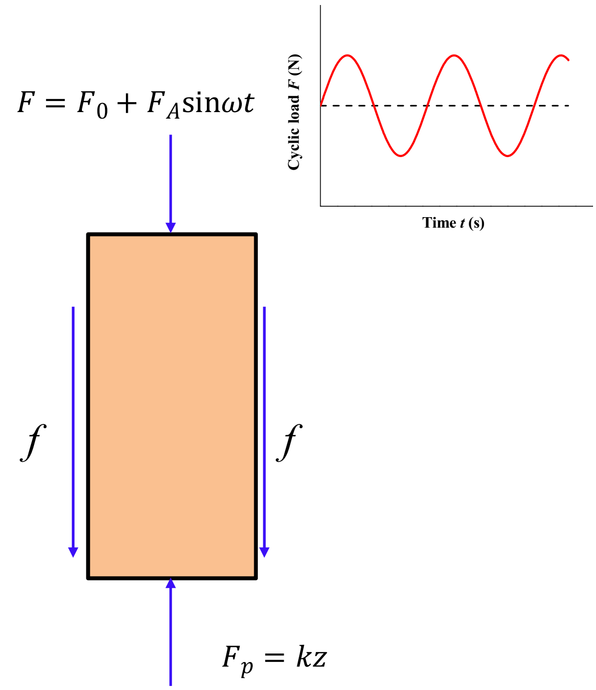

Fig. 1. Schematic diagram of stress analysis of studied system.

$$W_f = \int_o^t fvdt \tag{4}$$

In addition, kinetic energy E_k and elastic potential energy E_e can be calculated by the following formulas, respectively.

$$E_k = \frac{1}{2}mv^2 \tag{5}$$

$$E_e = \frac{1}{2}kz^2 \tag{6}$$

where, m is quality of studied object [kg]; v is the same as the above; k is restoring force coefficient, also known as the generalized stiffness [N/m]; z is displacement of deviation from the initial position [m].

The following work is to derive the vibration differential equation and solve it. We first establish a physical model of vibration system. Assume the studied soil object is a forced vibration system of a single degree of freedom with damping in the vertical direction, whose stress state under cyclic loads is shown in Fig. 1.

Thus, according to Newton's first law,

$$ma = m\ddot{z} = F - f - F_p \tag{7}$$

In which, a is vibration acceleration of system [m/s^2], $a = \ddot{z} = d^2z/dt^2$; F_P is restoring force of system, F_P=kz; others are the same as the above.

Damping of soil makes energy dissipate and lose in the process of vibration, and it could generally be divided into viscous damping and friction damping in engineering practice. However, their contribution to the dissipation of energy is not the same. It has been proven by fluid mechanics that viscosity resistance generated by viscous damping of media is proportional to vibration velocity of studied object and related to frequency; frictional resistance produced by friction damping is independent of vibration frequency and merely subject to displacement or strain. As the amount of energy dissipation is mainly related to frequency of wave [30,35,40], this paper only considers the impact of viscous damping to facilitate the calculation. Thus, the resistance f can be calculated by formula (8).

$$f = -cv = -c\dot{z} \tag{8}$$

where, c is coefficient of viscous resistance, and also known as the