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Prediction of lateral displacement of soil behind the reaction wall caused by pipe jacking operation

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ABSTRACT

The lateral displacement of the soil behind the reaction wall of an open caisson can affect the efficiency and safety of jacking operation and control. This paper focuses on the deformation induced within the soil mass behind the reaction wall used to support the jack. A numerical approach for shakedown analysis is first proposed utilizing the energy dissipation principle and its effectiveness is verified by one classic computational example. Combining a project involving parallel pipe jacking under the Guan River in Jiangsu, China, specific procedures for displacement prediction with the soil behind the reaction wall based on shakedown analysis are then given. After the reasonableness and necessity of proposed technique is justified by comparison with commonly used method, the dependence of the soil displacement on three important parameters is investigated: the thickness of the reaction wall, elastic modulus of the soil and the position changes of the reactive force. The proposed technique is a new way of predicting displacement with reasonable accuracy for the control of deformation in the soil behind the reaction wall, and the predicted results are valuable references for ensuring construction quality.

1. Introduction

Pipe jacking is a technique used to install an underground pipeline through a bore created by a shield-type driving machine from a starting pit (Shimada et al., 2004). It offers an economically attractive method of constructing underground pipelines, especially in urban areas, and eliminates the disruption and destruction generally associated with the traditional open-cut method. Pipe jacking technology has been used in various applications, such as sewer, oil and gas pipelines, electricity and telecommunications cable installation, because of these advantages (Sofianos et al., 2004; Shimada et al., 2006; Li et al., 2007). Open caissons are structures commonly used as working shafts in pipe jacking projects. During the jacking process, reactive forces caused by the insertion of the pipes are transmitted from the reaction wall to the soil behind the reaction wall of an open caisson. The soil behind the reaction wall is disturbed significantly if the jacking force is large enough. As a result, the support conditions of the open caisson change and can cause movement. In this way, the jacking forces are absorbed by the soil and result in its deformation, reducing the efficiency of the jacking operation. This scenario can cause serious soil damage and jacking failure. Therefore, it is important to study the deformation behaviour of the soil behind the reaction wall and obtain reasonable predictions of its deformation. This study can provide a theoretical basis for effective countermeasures to control the deformation of the soil behind the reaction wall, involving the rational choice of construction parameters, soil reinforcement and more. Currently, research efforts addressing the disturbance of pipe jacking construction on the soil behind the reaction wall have been relatively scarce. The existing literature (Sofianos et al., 2004; Wei et al., 2005; Mao, 2007; Milligan and Norris, 1996; Khazaei and S., 2004) has focused only on soil earth pressure calculations and jacking forces. Few publications exist on soil displacement predictions during pipe jacking construction, and soil displacement prediction is more complex than similar engineering problems because of the properties of variable repeated loads applied to it. The scenario's complex nature clearly requires a more effective theoretical model to simulate the actual deformation behaviour observed in practice.

The static shakedown theorem proposed by Melan (1938), together with the kinematic shakedown theorem proposed by Koiter (1960), is the cornerstone of the shakedown analysis of elasto-plastic structures under cyclic loading. Shakedown theory has become a useful tool in a wide range of practical engineering applications (Feng and Gross, 1999; Chen and Ponter, 2001; Benfratello et al., 2006; Hoang and Nguyen, 2008). The use of the shakedown theory can enable the long-term behaviour of a

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structure to be determined without resorting to a full incremental load–displacement analysis and make it possible to model the cyclic nature of the imposed loading, thereby increasing the reliability of the predictions and displacement response solutions.

The main contents and goals of the study were as follows. (i) Propose a numerical approach of shakedown analysis (Section 2). The present approach was established utilizing the energy dissipation principle as a shakedown criterion via special load paths. (ii) Combine a project involving parallel pipe jacking that passes under the Guan River in Jiangsu, China (Section 3), specific prediction procedures for lateral displacement based on shakedown analysis were given (Section 4). (iii) Use the proposed approach (Sections 2 and 4) to perform a displacement prediction of the soil behind the reaction wall in the project (Section 5). After the reasonableness and necessity of proposed technique was justified, the dependence of the lateral displacement on three key parameters was investigated in detail. Section 6 presents the conclusions made from this study.

2. A numerical approach of shakedown analysis

2.1. Shakedown concept

In the case of an elastic-perfectly plastic body subjected to load cycles that vary arbitrarily within given limits, if the load is larger than the elastic limit but less than a specified critical limit, then plastic deformation will occur in some part of the body. However, after a number of load cycles, the plastic deformation ceases to develop further and the body responds purely elastically to the remaining load cycles (see Fig. 1). If this occurs, then the body is said to experience shakedown (Carvelli et al., 1999).

Although the shakedown theory has been developed as part of the classical and computational mechanics of inelastic solids and structures, for various soils and granular materials, shakedown phenomena have also been observed in experimental studies (Garcia-Rojo and Herrman, 2005; Brown et al., 2008), and some numerical methods of shakedown analysis have been developed (Chazallona et al., 2009; Li and Yu, 2006; Werkmeister et al., 2004). Shakedown analysis could be used to directly evaluate the maximum deformation corresponding to a shakedown state under a known stress level by the avoidance of load history, which would enable the long-term behaviour of structures to be determined without resorting to tedious and computationally expensive step-by-step analyses. Thus, shakedown analysis can also model the actual deformation mechanisms observed in practice. The characteristics of shakedown theory make it particularly applicable to the analysis of soil displacement under variable repeated reactive forces. Its application can increase the reliability of the predictions and solutions developed during the design process and construction procedures for pipe jacking projects.

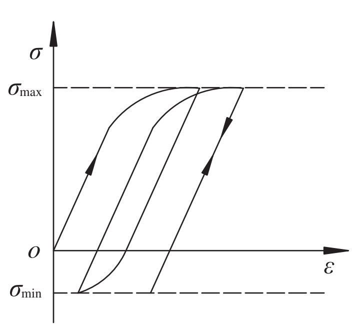

Fig. 1. Shakedown behaviour under repeated cyclic loads.

2.2. Shakedown analysis utilizing the energy dissipation principle

The method, which uses the concepts of work and energy to solve for the displacement, deformation, and internal force of a deformable solid, is collectively called the energy method (Guralnick et al., 1984). Using the energy method, Yala et al. (1993) investigated reinforced concrete framed structures subjected to cyclic loading, and developed a computer program to study shakedown. It is concluded from the research that shakedown is characterised by a scenario in which plastic yielding eventually ceases through bounded cumulative energy dissipation. The objective of this section is to extend the previous work from beam structures to continuous structures using the cumulative energy stored in the structure as a means of defining shakedown. In this section, combing the special load paths used by Zhang and Yang (1994), a numerical approach for shakedown analysis of continuous structures has been developed.

By definition, the load domain P represents a region in the variable space that governs the loading time history. Because this time history is not automatically predictable, any point belonging to P is assumed to represent a combination of external actions that can be performed an unlimited number of times at unknown instants according to an unknown sequence. For K independent generalised loads P_1, P_1,. . ., P_K, the load domain P, which represents a K-dimensional polyhedron, can be expressed as:

$$P = [P_1, P_2, ..., P_K]^T = \lambda[\mu_1 p_1, ..., \mu_K p_K]^T = \lambda\{\mu_k p_k\},$$
$$\mu_k^- \leqslant \mu_k \leqslant \mu_k^+ \quad (k = 1, 2, ..., K) \tag{1}$$

where μ_k denotes the amplitude coefficient of p_k with upper and lower bounds μ_k^- and μ_k^+, respectively, and λ is a common amplification factor (load factor). Let region P in the load variable space be affected by a homothetic transformation, with the reference frame origin acting as the pole. The central objective of the shakedown theory is to compute the safety factor or the value of the load domain amplification factor.Indicating strains in a discrete or discretized structure, total strain ε can be decomposed into:

$$\varepsilon = \varepsilon^e + \varepsilon^p \tag{2}$$

where superscript e indicating elastic and p plastic strains.

The increments of plastic strain at the end of one load cycle over the time interval $[nT, (n + 1)T]$ can be defined as:

$$\Delta\varepsilon_{ij}^p = \int_{nT}^{(n+1T)} \dot{\varepsilon}_{ij}^p dt \tag{3}$$

where T is the period of the load cycles and $\dot{\varepsilon}_{ij}^p$ is the plastic strain rate. After each load cycle on a body with volume V, let ξ be the generalised displacement increment, and the total work performed by the external loads can be calculated as:

$$\int_{nT}^{(n+1)T} P\dot{\xi}dt = W_e + W_p$$
$$= \int_{nT}^{(n+1)T} dt \int_V \sigma_{ij}\dot{\varepsilon}_{ij}^e dV + \int_{nT}^{(n+1)T} dt \int_V \sigma_{ij}\dot{\varepsilon}_{ij}^p dV \tag{4}$$

where $\dot{\xi}$ denotes the generalised displacement rate, $\dot{\varepsilon}_{ij}^e$ is the elastic strain rate, and W_e and W_p are the elastic work and plastic work, respectively. If $\dot{\varepsilon}_{ij}^p = 0$, the first term on the right-hand side of Eq. (4) vanishes after unloading due to the recovery of the elastic response, and the second term is also equal to zero. In this case, the residual stress field ρ_{ij} is time-independent and determined by the plastic deformation in early load cycles. Thus, the shakedown occurs in the given load range, and the cumulative dissipated energy in the space appears to grow over time within limits.

By substituting Eq. (3) into the second term of the right-hand side of Eq. (4), we obtain the plastic work of the load cycle: