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# Determination of traffic-load-influenced depths in clayey subsoil based on the shakedown concept

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ABSTRACT

The determination of the depth of traffic load influence is significant for pavement and embankment design on soft soil. In this study, a method based on strain-controlled criteria is presented to estimate the depths within which the behavior of a saturated clayey subsoil is affected by cyclic traffic loads. Based on the shakedown concept, the following depths of influence can be defined: (1) the threshold depth, beyond which the dynamic effect of the traffic loads is insignificant; (2) the plastic shakedown limit depth, within which the subsoil experiences noticeable and continuous deformation; and (3) the critical failure depth, within which the soil fails due to the accumulation of strain. This method for determining the depths of influence is advantageous because it is applicable to various soil types. The data required for this method consist of vertical stress responses along the soil profile and three cyclic stress limits of the soil. Based on the development of pore pressure and the dynamic strain behaviors during undrained cyclic triaxial tests, the following cyclic stress limits of the soft clay subsoil are determined: a threshold cyclic stress ratio $CSR_t$ of 0.03, a plastic shakedown limit stress ratio $CSR_p$ of 0.33 and a critical cyclic stress ratio $CSR_c$ of 0.44. These cyclic stress limits are used to determine the corresponding depths of influence, which are then used to implement ground improvements and strengthen the dynamic carrying capacity of the road structures.



## 1. Introduction

Differential settlement of subgrade soils is undesirable because it typically leads to road damage [1–4], e.g., pavement cracks, rutting, and uneven road surfaces. Subgrade soil settlement can be primarily attributed to two loads: the static load due to the weight of the embankment and the dynamic load due to traffic loading [1]. A common strategy for controlling the settlement is to minimize the embankment height [1], which reduces the static load. However, this strategy may have undesirable side effects, especially in the case of an underlying soft subsoil. The embankment and subgrade can be considered a buffer zone that greatly diminishes the dynamic stress and deformation induced by traffic loads [5–7]. As the thickness of this zone decreases, the diminishing effect decreases, allowing more dynamic stress to propagate into the soft subsoil and resulting in more severe settlement [5].

The current design practice converts the dynamic load into an equivalent static load [7–9]. This equivalent load is then combined with the weight of the embankment, comprising the total load for settlement prediction. In this method, the dynamic effect is overlooked, and the settlement might be under-predicted [9–11]. A dynamic load is fundamentally different from a static load in at least two aspects: (1) it has a greater stress response [6,12] and thus a deeper influence depth, and (2) it is characterized by accumulated deformation and internal forces [13–15]. Previous studies have found that there is a maximum depth of influence beyond which the dynamic stress is negligible for practical purposes [15–18]. However, above the maximum depth of influence, the dynamic stress and strain in the subsoil will not completely dissipate in the unloading state and will accumulate. The accumulation effect of the traffic load may eventually cause excessive settlement of the pavement and subgrade systems [1–4].

Substantial efforts have been devoted to the determination of the maximum depth of influence, and various criteria have been proposed [10,11,15–19]. The existing methods can be divided into the following groups: stress criteria, strain criteria, and empirical criteria. They are briefly introduced as follows:

(1) Stress criteria: Huang et al. [16] and Li et al. [17] defined the depth at which the additional dynamic stress is equal to 1/10 of the overburden pressure as the maximum depth of influence. They further concluded that the maximum depths of influence

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were approximately 6.0–8.0 m and 6.0–14.0 m under non-overloaded and overloaded conditions, respectively.

(2) Strain criteria: Chou et al. [18] stated that the stress criteria cannot completely reflect the influence of the traffic loads on roadbed subsidence. They suggested that the maximum depth of influence for soft soil is the depth at which 0.001% vertical strain occurs. Chai and Miura [15] proposed an empirical equation to calculate the dynamic strain of soil. They concluded that the depth significantly influenced by traffic loads in sensitive Ariake clay subsoil was approximately 6 m.

(3) Empirical criteria: Hu [11] empirically estimated that soil is significantly influenced by the traffic load to a depth of 10.0 m. Mei et al. [19] used a finite element method to obtain a curve of settlement versus depth, determining the critical failure depth of influence and the maximum depth of influence based on the shape and inflection points of the curve. Hu et al. [10] considered the depth below which the deformation was less than 2 mm to be the maximum depth of influence.

Although the stress in the subsoil can be obtained using measurement methods or numerical methods, it is not ideal to adopt stress as a criterion for determining the depth of influence because the stress–strain relationship is not monotonic for some soil types. The empirical methods are advantageous for local projects; however, due to the complex geological process from one region to another, soil properties vary widely regionally so that one empirical criterion cannot be directly applied or extended to other areas [5].

Ideally, the stability of subsoil should be evaluated based on the strain behavior [3–5,20]. Studies have tended to obtain in-situ deformation and strain data using modeling methods [10,11,18] based on some postulated conditions and the static properties of the material. Unfortunately, the calculated strain is hard to be verified by real measured values. The difficulties of measuring in-situ soil strain limit the application of strain criteria to estimate the depth of influence.

Moreover, using a general maximum traffic-influenced depth cannot sufficiently reveal how the subsoil behaves under different dynamic stress levels. By considering the shakedown concept and the exposure degree of subsoil, the depth of influence can be categorized into the following levels: (1) the critical failure depth, (2) the plastic shakedown limit depth and (3) the threshold depth.

The primary objective of this study is to develop a method to determine the three depths of influence. The method is strain-controlled and is expressed as a function of stress. The required data and parameters include the cyclic behaviors of the subsoil under various cyclic stress ratios (CSRs) and the vertical stress responses along the soil profile. The threshold cyclic stress ratio ($CSR_t$), plastic shakedown limit stress ratio ($CSR_p$) and critical cyclic stress ratio ($CSR_c$) of the subsoil are obtained based on the pore pressure evolution and cyclic strain behavior in triaxial tests. The three depths of influence can be estimated using a combination of the dynamic stress responses and the cyclic stress ratio limits (i.e., $CSR_t$, $CSR_p$ and $CSR_c$).

## 2. Shakedown concept and depths of influence

### 2.1. Shakedown concept

The shakedown concept has been used to describe the behavior of engineering structures under cyclic loading [4,14]. The term shakedown indicates that the plastic deformation of a structure tends to stabilize at a certain level under a finite number of loading cycles. If the magnitude of cyclic stress exceeds a critical level, then the plastic deformation in a structure accumulates as the number of loading cycles increases, and the structure eventually collapses due to excessive deformation.

The static shakedown theorem proposed by Melan [21] and the kinematic shakedown theorem proposed by Koiter [22] constitute the cornerstone of shakedown theory for elastic–plastic structures under cyclic loading [8]. Subsequently, Sharp and Booker [23] applied the shakedown concept to evaluate the service life and ultimate shakedown strength of pavement. Werkmeister et al. [4] stated that the shakedown method could provide a powerful tool for material assessment in pavement design. Kooststra et al. [24] investigated the deformation characteristics of several types of soil based on the shakedown concept.

According to the shakedown concept, the behaviors of materials under cyclic loading can be classified into the following five stages [4], as illustrated in Fig. 1:

(1) Purely elastic: the repeatedly applied stress is sufficiently small that no local elements in a material reach a yield

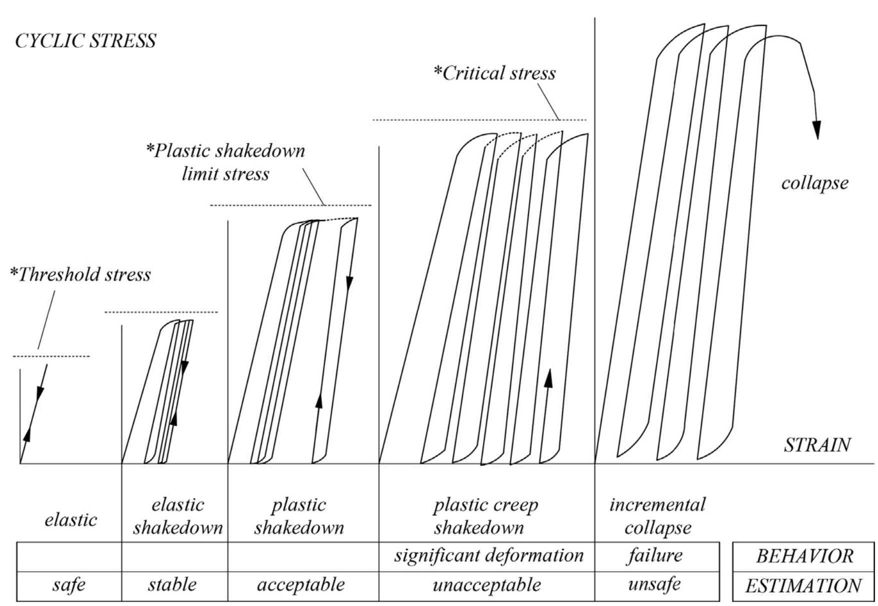


**Fig. 1.** Typical shakedown behavior of a material under cyclic loading (modified from Werkmeister et al. [4]).