Long term accumulation of deformation in granular soils under multi-axial cyclic loading

Accumulation de déformation à long terme dans les sols granulaires sous chargement cyclique multi-axiale

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ABSTRACT

Repeated small amplitude dynamic loading of the soil in the vicinity of buildings, as arising from traffic or construction activities, may cause differential foundation settlements and structural damage. In this paper, an accumulation model for settlements due to vibrations at small strain levels in granular non-cohesive soils is proposed. It is assumed that the dynamic part of the stresses is small with respect to the static part. As plastic deformation in the soil is only observed after a considerable amount of dynamic loading cycles, only the accumulation of the average plastic deformation is considered. The accumulation model is calibrated by means of cyclic triaxial tests. However, the stress conditions in the cyclic triaxial tests are an approximation of the complex loading paths in the soil under traffic induced vibrations, that are intrinsically multi-axial and transient signals. Therefore, a rainflow counting algorithm is used to relate traffic induced vibrations to the triaxial test conditions. The model is applied to compute the differential settlement of a two-story building founded on loose sandy soil under repeated passages of a truck on a nearby speed table. Results demonstrate that vibrations may give rise to significant long term settlement of structures.

RÉSUMÉ

Un chargement dynamique répété du sol à proximité de bâtiments, dû au trafic ou à des activités de construction, peut produire des tassements différentiels et des endommagements structuraux. Dans cet article, un modèle est proposé pour estimer l'accumulation de déformations dans les sols granulaires non-cohésifs sous chargement dynamique répété de basse amplitude. Il est supposé que la partie dynamique des contraintes est négligeable par rapport à la partie statique. Comme la déformation plastique dans le sol n'est observée qu'après un nombre important de cycles de chargement dynamique, seule la valeur moyenne de la déformation plastique est considérée. Le modèle d'accumulation est calibré à l'aide d'essais triaxiaux cycliques. Toutefois, les conditions expérimentales, liées à l'utilisation d'essais triaxiaux cycliques, diffèrent des conditions de chargement complexes rencontrées dans le sol sous l'effet de vibrations, induites par le trafic, qui sont intrinsèquement des signaux multiaxiaux et transitoires. Par conséquent, un algorithme rainflow est utilisé pour relier les vibrations induites par le trafic aux conditions de l'essai triaxial. Le modèle est appliqué pour calculer le tassement différentiel d'un bâtiment sous l'effet du passage répété d'un camion. Les résultats montrent que les vibrations peuvent donner lieu à d'importants tassements à long terme des structures.

Keywords: Strain accumulation model, low level vibration, granular soil, long-term behavior

1 INTRODUCTION

Repeated dynamic loading of soils under low amplitude vibrations is a subject of growing interest [1, 2, 3, 4]. Low amplitude ground vibrations are generated by road and railway traffic, subways, construction works or heavy industry. These vibrations propagate through the soil and

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impinge on the foundations of nearby structures. For small amplitude dynamic loading with resulting strain amplitudes below 10^{-4}, no (measurable) residual deformation is observed for a single load cycle and the constitutive behavior of the soil can be described by linear visco-elastic models. After a large numbers of events, however, permanent deformation is observed in many cases.

To describe the long term accumulation of deformation, a number of constitutive models have been developed that only describes the accumulation of the average permanent deformation per load cycle. In this paper, the accumulation model developed by François et al. [2] and Karg et al. [5] is employed.

The results of cyclic triaxial tests are used to calibrate phenomenological models for the calculation of foundation settlements. However, the stress conditions in the cyclic triaxial tests are only an approximation of the complex loading paths in the soil under traffic induced vibrations, that are intrinsically multi-axial and transient signals.

Niemunis et al. [6] have proposed a methodology to relate complex loading signals to the cyclic loading amplitude in a cyclic triaxial test by means of a tensorial amplitude. However, the tensorial amplitude is not particularly suited for transient signals, since only the peak value of the time history of the signal is accounted for, neglecting the fact that a transient signal is a composition of cycles with small and large amplitudes.

Therefore, an alternative methodology is proposed, based on a rain flow counting algorithm, decomposing the transient loading signal into a number of equivalent sinusoidal signals.

The proposed accumulation model is implemented in a finite element framework. The model is applied to compute the differential settlement of a two-story building founded on loose sandy soil under repeated passages of a truck on a nearby traffic plateau.

2 RAINFLOW COUNTING ALGORITHM

The stress conditions in the cyclic triaxial tests are an approximation of the complex loading paths in the soil under traffic induced vibrations, that are intrinsically multi-axial and transient signals. In order to demonstrate this, the free field vibrations during the passage of the truck over a speed table is computed with the numerical prediction model proposed by Lombaert [7].

A two-axle truck with a wheel base of $5.2\,\mathrm{m}$ passes at a vehicle speed $v = 50\,\mathrm{km/h}$ on the speed table. Figure 1 shows the vertical displacement at the point $\{x = 8, 0, z = -1\}^{\mathrm{T}}$ in the free field. The four peaks correspond to the front and rear axles driving on and off the speed table. The stress and strain history during the passage of the truck is follows a similar complex loading path.

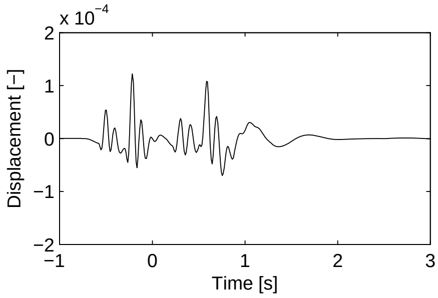

Figure 1. Displacement history at the point $\{x = 8, 0, z = -1\}^{\mathrm{T}}$ in the free field.

In order to adopt the one-dimensional accumulation model to the multiaxial loading as observed in practice, the loading history should be represented as a one-dimensional measure of stress or strain. In this paper, the signed Von Mises strain is used, which is defined as the Von Mises strain that takes the sign of the maximum absolute principal strain. Figure 2 shows the signed Von Mises strain history at the point $\{x = 8, 0, z = -1\}^{\mathrm{T}}$ (Figure 4) in the free field.

Next, a rainflow counting algorithm is applied that decomposes the signed Von Mises strain history into a number of simple cyclic loads [8]. Figure 3 shows the histogram of strain amplitude for a single passage of a truck as obtained with the rainflow counting algorithm. Miner's rule [6] is applied that states that the sequence of the load cycles has no influence on the total accumulation of deformation.

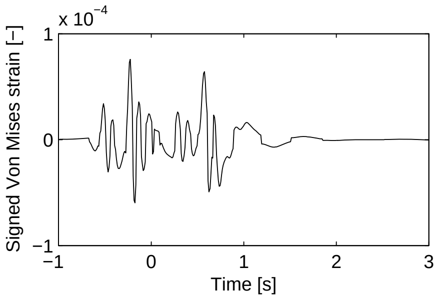

Figure 2. Signed Von Mises strain at the point $\{x = 8, 0, z = -1\}^{\mathrm{T}}$ in the free field.

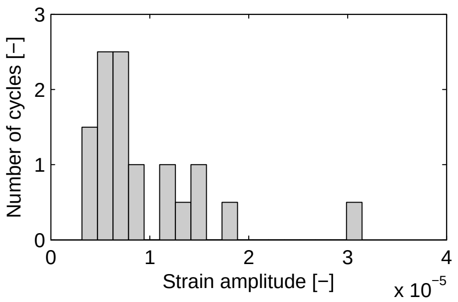

Figure 3. Histogram of strain amplitude for a single passage of a truck as obtained with the rainflow counting algorithm.

Current research involves the validation of the proposed rainflow counting algorithm. In order to apply multi-axial loading paths in the cyclic triaxial test, the classical setup is currently being modified where both the hydrostatic confining pressure and the vertical stress on the soil sample are independently and cyclically varied.

3 NUMERICAL EXAMPLE

In this section, the accumulation model is used to assess the settlement of a masonry building due to repeated vehicle passages. Figure 4 shows the structure, located at a distance $l_{\mathrm{r}} = 10\,\mathrm{m}$ from a road.

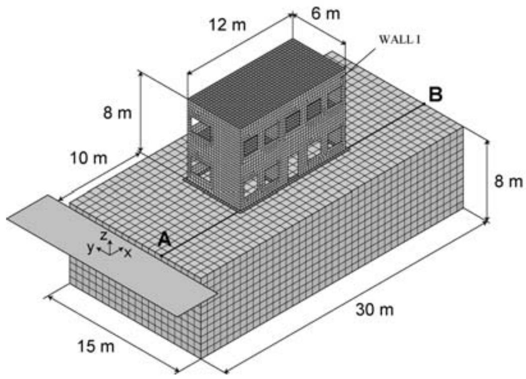

Figure 4. The masonry building excited by the traffic induced wavefield.

The peak particle velocity decays as $1/\sqrt{x}$ where x is the horizontal coordinate perpendicular to the road, as a result of geometric attenuation of Rayleigh waves. The strain amplitude also decays with this factor.

The building has dimensions $8 \times 12 \times 6\,\mathrm{m}$ (Figure 4). The structure is modelled with 4-node shell elements with an element size $l_{\mathrm{el}} = 0.30\,\mathrm{m}$. The masonry building is founded on a layer of loose sandy soil, for which the accumulation model is adopted.

After the application of the gravity load, a total number of $N = 10^6$ vehicle passages is considered, and the quasi-static response of the soil and the structure is computed with the finite element package ANSYS. Figure 5 shows the deformation of the line AB in the (x,y)-plane (Figure 4) after the application of the gravity load, and after the passage of 10000, 500000 and 1000000 vehicles. The initial vertical displacement is much smaller than the vertical displacement after the load events have taken place. Furthermore, most of the soil deformation takes place during the first 10000 load events, which is in correspondance with the logarithmic shape of accumulation curves of cyclic triaxial tests.

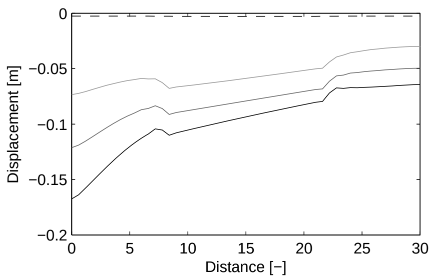

Figure 5. Vertical displacement along the line AB before accumulation (dashed line), and after 10 000 vehicle passages (light grey line), 500 000 vehicle passages (dark grey line) and 1 000 000 vehicle passages (black line).

As a result of the differential foundation settlement, the stress distribution in the structure is modified. Figure 6a shows the first principal stress in wall I after the application of the gravity load, and figure Figure 6b shows the first principal stress after the passage of 1000000 vehicles. The differential foundation settlement causes a global bending of the wall. At the bottom of the wall, the principal stress increases to reach a maximum value of about $0.25\,\mathrm{MPa}$ and may result in cosmetic damage.

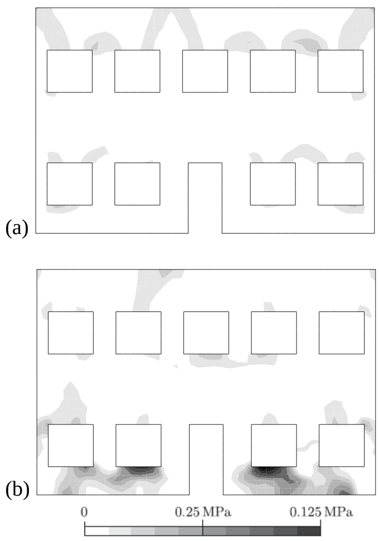

Figure 6. First principal stress in wall I (a) after the application of the gravity load and (b) after the passage of 1000000 vehicles.

4 CONCLUSION

In this paper, an accumulation model for deformation in granular soils under multi-axial cyclic loading has been presented. The accumulation model is calibrated by means of cyclic triaxial tests. However, the stress conditions in the cyclic triaxial tests are an approximation of the complex loading paths in the soil under traffic induced vibrations, that are intrinsically multi-axial and transient signals. Therefore, a rainflow counting algorithm is used to relate traffic induced vibrations to the triaxial test conditions. The model has been applied to compute the differential settlement of a two-story building founded on loose sandy soil under repeated passages of a truck on a nearby speed table. Results demonstrate that vibrations may give rise to significant long term settlement of structures.

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