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DYNAMIC COMPACTION OF COHESIVE SOILS – THEORETICAL ASPECTS AND MODELING

DYNAMICZNE ZAGĘSZCZANIE GRUNTÓW SPOISTYCH – ASPEKTY TEORETYCZNE I MODELOWANIE

Abstract

The principles of dynamic compaction of soils are presented in the paper, along with a short description of its usefulness for cohesive soils. The main topic of the article is the description of ways of modeling the phenomenon related to dynamic compaction. This is based on experimental data and on recently developed computer models using the Finite Element Method. Existing simplified 'perfectly flexible plastic' model is presented and used for computer modeling. The model does not capture the highly plastic and nonlinear behavior of cohesive soils under dynamic compaction. Additionally, a modified Cam-Clay constitutive model will be briefly described, which can address the above mentioned issues. Computer modeling method of the phenomenon will be discussed, together with a short description of the dynamic characteristics of the process.

Keywords: dynamic compaction, cohesive soils, Final Elements Method

Streszczenie

W artykule przedstawiono podstawy zagęszczania dynamicznego wraz z krótkim opisem jego stosowalności dla gruntów spoistych. Podstawowym tematem artykułu jest jednakże opis modelowania tego zjawiska. Jest on oparty na danych doświadczalnych oraz, ostatnio rozwiniętych, metodach opartych na Metodzie Elementów Skończonych. Przedstawiono podstawy modelu doskonale plastycznego (stosowanego w modelowaniu komputerowym). Model ten nie odzwierciedla jednak wysoce plastycznego i nieliniowego zachowania gruntów spoistych pod wpływem dynamicznego zagęszczania. Zmieniony model konstytutywny Cam-Clay został krótko opisany, może on do pewnego stopnia rozwiązać powyższe problemy. Zostaną przedstawione sposoby praktycznego modelowania zjawiska, a także podstawy komputerowego modelowania zjawiska, wraz z dyskusją dynamiki procesu.

Słowa kluczowe: zagęszczanie dynamiczne, grunty spoiste, metoda elementów skończonych

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Notation

c – cohesion [kPa]
C_c – *w*ave velocity [m/s]
d – crater depth [m]
D – tamper diameter [m]
E – elastic modulus [kPa]
f – wave propagation frequency [Hz]
F – force [MN]
G – shear modulus [kPa]
H – tampering height [m]
M – constrained modulus [kPa]
t – time [s]
W – tamper weight [Mg]
H – tampering height [m]
λ – wave length [m]
ρ – density [Mg/m^3]
υ – Poisson's ratio [–]
φ – friction angle [deg]
ψ – dilation angle [deg]

1. Introduction

Dynamic compaction (DC) is an engineering process used to increase structural bearing capacity of soils – for building purposes (in particular – foundation soils straightening).There are a few distinct types of that process, but only DC using heavy tampering issues is shortly discussed in this paper. It was invented a long time ago, but in modern practice it has been developed by Louis Mennard and his commercial company MENARD Corp [1–3].

The process can be described as follows: the tamper (usually a steel cylinder of 2–3 meters of diameter, several tons of weight) is raised up to a pre-calculated height using a special crane to be then released. It gains speed quickly (and thus kinetic energy) and then it hits the ground, compacting it. A crater forms, sometimes of a depth of 1m or more. The structural parameters of soils are then greatly improved (albeit only in the vicinity of actual impact site). The procedure is repeated for neighbouring places following a pre-planned regular pattern. Sometimes more than one hit of the tamper is required. The procedure is referred to as the "multiple passes" approach. The entire area is leveled afterwards, using bulldozers, and sometimes other materials (gravels) are introduced [3, 4].

The following parameters are of main interest: the tamper weight W, the tampering height H, the tamper diameter D of the bottom area, the crater depth d, the type of soil to be treated, including its actual layered structure.

This technology is used for improvement of foundations for large-scale projects, where no other known technology can be used in an economical way. It has been successfully utilized for granular soils, where its functioning is quite well understood. It can be used for fine soils as well, but the physics behind this is far more complicated [4].

From an engineering point of view, there are three main differences between Dynamic Compaction of granular and fine soils. Firstly, there are water-pore pressure issues. In coarse, granular soils after tampering, water is filtered away through small pores between the grains. The water pressure slowly decreases after that. This process can take a few months to complete. In fine soils it is, however, hardly possible. Water will not filter through soils that easily. When the pore water pressure is high enough, it creates cracks in the body of soil around the point of tampering, so that water may escape. Sometimes this flow is so intensive that shallow marshes or puddles are visible on the surface after tampering [2, 4, 5].

Secondly, the situation with compressed gas bubbles is different for fine and coarse soils. In fine soils a large part of air trapped in the soil pores does not escape during dynamic compaction, and while this will not crack the soil body, it is being compressed, thus the overall volume of pores can be decreased, resulting in some soil compaction [2].

Thirdly, there is a difference between fine and coarse soils regarding remoulding issues. With great stresses caused by DC the internal structure of the soil may be destroyed, so at that point the soil may behave like a liquid. This happens when the stresses overcome the forces holding the grains together. This phenomenon is called a “soil liquefaction”. After some time, however, the soil “remoulds” as it returns to the solid state, albeit with different parameters. This may lead to a general improvement of the soil condition (as it gets compacted that way), but if fine soils are surrounded by significant inlets of coarse material (that is fine soils are “supported” by a coarse “skeleton”) liquefaction of the fine part will be of no use, as it shall “remould” into the same shape as before the treatment. Because of that, DC must be performed in such a way that liquefaction of coarse material happens before, or nearly at the same time, as of the fine one [2].

Dynamic Compaction can thus be utilized for both granular, and fine soils, or a combination of both, but there is a need for good modeling tools and guidelines. Louis Mennard has proposed some rough estimations [2, 3], based on actual engineering practice, but a more refined approach is needed, because not all soils can be effectively treated that way. The other problem is that DC is an efficient, though costly technology. Excess tampering may be unnecessary representing wasted time and money, or even counterproductive, since a poorly designed DC process may even weaken the soil. A lot of energy is put into the ground in a dynamic way. This may cause serious problems for neighbouring buildings which poses a risk of cracking or even failing. An estimation of the allowable distance from the nearest structure is therefore very important.

2. Common modeling approaches

The described phenomenon has been studied extensively. Some of the main findings and theories used are summarized below. In most cases the calculations are done using the Finite Element (FE) method.

As a first step for modeling of dynamic consolidation of soils, some models based on the linear equivalent viscous-elastic theory are introduced and implemented. However, they are not realistic for a medium like soils characterized by complicated behavior under dynamically changing pressures, among other issues. Some parameters however, may be extracted from that models for further use. Models based on the elastic principle are much better as they can capture the nonlinear behavior under changing and variable stress paths. There is still a serious problem with capturing and modeling of dynamic processes, including Dynamic Compaction [6].

The linear viscoelastic model, yet only partially useful, has one big advantage: only one stiffness matrix is needed for each time step. The equivalent for elasto-plastic models are much more complicated. Moreover, their implementation is more difficult [6].

To be able to solve these problems simultaneously, a new approach was referred to as the hypo-plasticity model. It was developed for stress-strain under simple loading. Then it was extended to more complicated loadings.

The model is based on dividing an effective stress tensor so that the spherical and the deviator stress which determine the behavior are seen. The theory was implemented into the FE code, and some reasonable results were obtained [6], but only for saturated sand foundations (although the authors of the method have stated that the model had also been verified using triaxial tests on silty clays).

Another widely used model is a Cam-Clay plasticity model. It was developed only for deformation and strain analysis of partially or fully saturated granular soils, using three-phase continuum theory [7].

Firstly, the energy expressions for the constitutive models are given. They are then related to effective stresses and deformations of the soil matrix, the pressures and the volume changes. Also, perhaps most importantly, they are linked to the seepage forces and the corresponding pressure gradients. The dissipation inequality is then calculated as well as condition of convexity of the yield function [7]. Next, conditions describing deformation bands for drained and undrained states are given. Finally, specific constitutive models for partially saturated soils have been developed, taking into account the calculated plasticity of the media. An interesting point is that the matrix suction is treated as another strain-like variable. Again, the model can only be partially used for fine soils, or for a mixture of different types of soils, under dynamic loads.

3. Force – load function

Another approach was proposed in [8]. Here, to overcome the general problem of dynamic loads, a different modeling tool has been developed. A specially constructed force-time function was superimposed on a fairly classic elastic model. This has led to a hybrid model, which was then introduced into the widely used Finite Element Method (FE) software. This approach is especially interesting for the author, although another software is to be used, named Z_SOIL v13.09 2d. This software is widely used for various tasks involving foundations analysis in different conditions. It has become an industrial standard for FE analysis. Being able to model DC that way, shall greatly increase the usefulness of the software referred to [8]. This is, however, a model for coarse soils.

The proposed function [8] consists of two parts: The left (ascending) part and the right (descending) part. Both are chosen to provide the composite characteristics of the phenomenon. The shapes of the two parts of the plot were based on both experimental and analytical data.

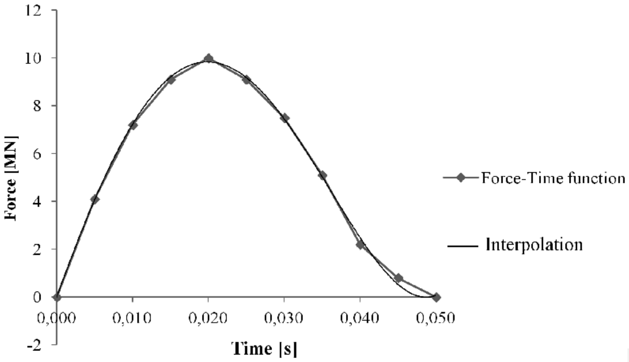

Fig. 1. Force-time function, along with the interpolation plot

To simplify the analysis an interpolation function is proposed (Fig. 1), using the following polynom:

$$F(t)=10000000t^{4}-747786t^{3}-8715.6t^{2}+873.15t+0.0042 \tag{1}$$

where:

t – denotes the time [s].

The function was based on regeresion analysis of the available data.

The figure shows that main differences between the lines (original data and interpolation) occurs in the very last part (about 0.045s). This can be easily rectified by using a more complicated polynominal function, or another type of interpolation, but it seems to have no big impact on the results.

4. FE model

To build a working model, boundary conditions must be specified. The Figure 2 shows the original plot [8] together with the author's implementation of this plot using Z_SOIL. (Fig. 2). The model is axi-symmetric.

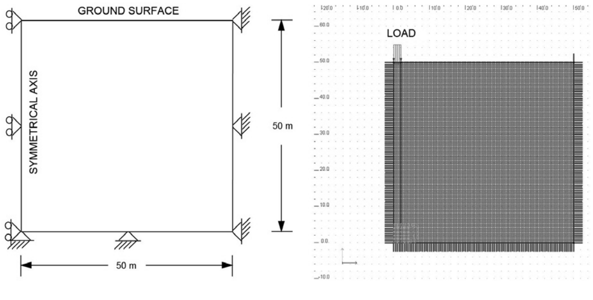

Fig. 2. Boundary conditions for modeling [8] (left), as used in Z_SOIL software suite (right)

This is a provisional model, based on [8], for coarse soils. The soil parameters used are: $E = 5000$ kPa, $\varphi = 25$ deg, $\psi = 5$ deg, $c = 5$ kPa, $\nu = 0{,}35$, $\rho = 1.8$ mg/m^3. Some other data were calculated: $M = 8025$ kPa, $G = 1852$ kPa, $Cc = 66.8$ m/s, wave propagation frequency for $f = 10$ Hz, $\lambda = 6.7$ m. They were used for determination of the size of FE mesh and mesh density identification.

5. Conclusions

Dynamic compaction technology has been known for some time now. It has been successfully used for different conditions, however an advanced tool for a correct design of the process is needed, especially for fine soils.

A proposed polynominal force-time function in its current form can be a meaningful step for formulating better modeling tools for dynamic loads assessment.

The results obtained by the Z_SOIL model differ from the expected deformations and settlements. This may mean that the model will have to be modified taking into account the highly nonlinear behavior of soils. The next step will be the improvement of the Z_SOIL model and its implementation for cohesive soils. It is emphasized, however, that much more work is required to attain a useful model for fine soils under dynamic loads, including the multiple-passes case.

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