Abstract. Oscillatory soil compaction implies a complex soil-roller interaction. Notwithstanding its benefits (e.g. through the less harmful effects on the adjacent built environment) this type of soil compaction has been less investigated in the past, by comparison with other type of dynamic soil compaction, e.g. vibratory roller compaction. Thereby, the paper aims at describing the numerical modelling of dynamic roller-soil interaction in the case of soil compaction with oscillatory rollers.

Keywords: dynamic soil compaction, oscillatory drum, dynamic roller-soil interaction

1 INTRODUCTION

During the past few decades, dynamic soil compaction has captured the attention in the field of geotechnical engineering. The research efforts were generally focused on experimental device developments and field testing, while the analytical approach of soil compaction investigations developed into sophisticated compaction technology marked with qualitative compaction indices. However, the heretofore developed analytical models oversimplify the dynamic roller-soil interaction and fail to describe the dynamic compaction processes. Thus, there arises the necessity of more efforts to be directed to developing robust computer models so that dynamic soil compaction can easily be simulated. Moreover, based on the available literature on soil compaction, it seems that very little work has been conducted for understanding oscillatory soil compaction in geotechnical engineering. This type of compaction implies an even more complex soil-roller interaction. Notwithstanding its benefits (e.g. through the less harmful effects on the adjacent built environment) the oscillatory soil compaction has been less investigated in the past, by comparison with other type of dynamic soil compaction, e.g. vibratory roller compaction (Adam, 1996) or a horizontally adjusted vario roller (Kopf, 1999). Thereby, the current paper aims at presenting a numerical modelling of dynamic roller-soil interaction in the case of soil compaction with oscillatory rollers.

2 SOIL COMPACTION WITH OSCILLATORY ROLLERS

Broadly, if the dynamic excitation is determined in advance, the modelling of prescribed dynamic loading can be easily achieved. The torsional motion of the oscillatory drum is caused by two opposed, rotating eccentric masses, which shafts are mounted eccentrically but point symmetric to the drum axis. Through oscillatory soil compaction, dynamic horizontal shear forces are induced in the contact area between the drum and the soil. Thus, it can theoretically be described by a two-degrees-of-freedom system (Adam and Kopf, 2000) considering the interaction between drum and soil, combining both components. At the time the maximum friction force between the drum and the soil surface is reached, the oscillatory excited drum starts slipping. This circumstance is to be considered in the so-called "stick-slip model" (Kopf, 1999). Consequently, two operating conditions of the torsional excited drum can occur:
the drum and soil stick, when the shear contact force is smaller than the maximum friction force: \( |F| \leq (G \cdot \mu) \) where, \( F \) is the shear force developed at the contact between the drum and the soil surface, \( G \) represents the total vertical force acting on the contact area and \( \mu \) denotes the friction coefficient between the two surfaces in contact.

the drum starts slipping, when the shear contact force is equal to the maximum friction force: \( |F| = (G \cdot \mu) \)

In addition, an appropriate contact formulation is necessary in order to model the soil–roller interaction. The finite element modelling of the above stated aspects is to be further presented in the paper.

The propelling of the roller results in large rigid body motion, which should also be taken into account in the numerical simulations. However this shall not play the main role in the interpretation of the results, since the oscillatory excitation of the drum is the aim of the analysis. Thus there arrives the need of a large time simulation, in order for the rigid body motion to be damped away and reach the so-called “steady state”, resulting in a prevalent oscillatory excitation.

3 NUMERICAL MODELLING CONCEPTS

The problem above described has been analysed using the finite element software ABAQUS Standard (ABAQUS, 2013). Figure 1 presents the finite element discretization adopted. In the vertical direction, the FE model extends 6.5m and in the horizontal 15m. The model is bounded with infinite elements (Lysmer and Kuhlemeyer, 1969) which are intended to provide the “quiet” boundaries, by damping the incident waves arriving to them.

The Finite element analysis consists of three stages: the geostatic stress state computation assuming the earth pressure coefficients at rest \( k_0 \) defined in Table 1; the contact initialization between the drum and the soil and the proper oscillatory soil compaction. The second and last steps of the simulation are conducted as dynamic analysis and within these, the viscous damping of the soil has been modelled via the Rayleigh damping approach, in which the discrete damping is accounted as a linear combination of the mass and stiffness of the material. The two Rayleigh coefficients \( \alpha_R \) and \( \beta_R \) for the soil have been computed according to the double frequency method as suggested by Lanzo et al.
(2004). This was acquired by assuming a constant soil damping ratio, $\zeta=20\%$ for the first natural frequency $\omega_1$ and for a frequency $\omega_n=n\times\omega_1$, where $n$ is the first odd integer larger than the ratio $\omega_n/\omega_1$.

The contact interaction between the drum and the soil is defined based on the surfaces of the two bodies and it was prescribed as dry friction with a coefficient of friction $\mu=0.30$. One surface was defined along the top edge of the compacted soil layer and another along the outer surface of the drum.

### 3.1 Roller modelling

Only the outer shell of the oscillatory drum is modelled as rigid body having its reference point in the centre of the drum. Finite elements of 10mm×22mm having the density of steel ($\rho=7850\text{kg/m}^3$) were distributed along the diameter of the drum. Moreover, in order to achieve the mass moment of inertia of the real drum, the difference compensating up to its real values was assigned to the rigid body. A dead load of $G=4.4\text{tonnes}$ acting on the central axis of the drum is applied in the reference point of the rigid body. This summarizes the vertical static action of the roller frame on the oscillatory drum.

![Diagram](image)

**Figure 2.** Model of the oscillatory roller: finite element model of the roller (left) and spring-dashpot system properties dependence on the frequency (right)

In reality, the oscillatory drum is additionally equipped with a hydraulic system intended to help it propel with a constant velocity in different soil condition. The power developed by this system, as also the magnitude of the propelling moment acting the drum, mainly depends on the stiffness of the compacted soil and the friction coefficient between this and the drum. In the finite element analysis this is also simulated by acting the drum with a constant propelling moment ($M_p$ in Figure 2). For the current soil stiffness and friction coefficient, the value of the propelling moment was set to a value of $M_p=1\text{kNm}$. This was established based on a parametric study of the parameters influencing it and it should be mentioned that this is out of scope of the present paper.

The torsional motion of the oscillatory drum is caused by two opposed, rotating eccentric masses, which shafts are mounted eccentrically but point symmetric to the drum axis. This is equivalent to a $M\cos(\omega t)$ oscillatory roller excitation which acts in the axis of the drum as presented in Figure 2. Hence, a periodic harmonic moment with a frequency of $f=39\text{Hz}$ and an amplitude of $A=54\text{kNm}$ is applied to the reference node of the rigid body simulating drum oscillations.

Aiming at a realistic simulation of the roller action on the drum, the latter is connected through a spring-dashpot system to a reference point described by a constant velocity $u'(t)=4\text{km/h}$ constraint. Furthermore, the properties of this system were derived from the conditions of dynamically decoupling it from the roller. With respect to this, the stiffness of the spring and the dashpot
coefficient are related to an eigenfrequency of the system in the range of $f_{s-d}=1-3\text{Hz}$ and damping ratio of $\zeta_{s-d}=10\%$, whose dependence on the frequency is depicted by Figure 2.

### 3.2 Soil modelling

The aim of the current modelling is simulating the compaction behaviour of a sandy soil layer resting on an elastic subgrade. The mechanical soil parameters are presented in Table 1. Usually, large shear strains occur in the contact zone between drum and soil, involving plastic deformations and even soil liquefaction effects (Adam and Kopf, 2000), resulting in soil compaction. In this context, theory of elasticity cannot efficiently describe the behaviour of soil in contact with the drum. Hence it requires modelling by different tools like theory of plasticity and elasto-plastic constitutive soil behaviour simulation.

At this rate, two different constitutive models have been adopted in the current modelling: the linear-elastic Hook’s constitutive law was meant to model the behaviour of the subsoil layer and the infinite media and the modified Drucker-Prager Cap model was employed for simulating the behaviour of the sandy soil (to be compacted). Hook law has been intensively used in solving different geotechnical problems, as long as the Drucker-Prager Cap model has found little use in this field, though it fits well to the simulation of soil compaction due to its inelastic hardening mechanism.

Table 1. Soil layers properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>Parameter</th>
<th>Unit weight</th>
<th>Young’s Modulus</th>
<th>Poisson’s ration</th>
<th>Cohesion</th>
<th>Friction angle</th>
<th>Cap eccentricity</th>
<th>Coefficient of earth pressure at rest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>[kN/m$^3$]</td>
<td>$E$ [MPa]</td>
<td>$\nu$ [-]</td>
<td>$d$ [kPa]</td>
<td>$\beta$ [-]</td>
<td>$R$ [-]</td>
<td>$k_0$ [-]</td>
</tr>
<tr>
<td>Compacted soil</td>
<td>19</td>
<td>30</td>
<td>0.30</td>
<td>0.20</td>
<td>53.08</td>
<td>0.20</td>
<td>0.455</td>
<td></td>
</tr>
<tr>
<td>Elastic subsoil</td>
<td>22</td>
<td>250</td>
<td>0.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.429</td>
<td></td>
</tr>
<tr>
<td>Infinite media</td>
<td>22</td>
<td>250</td>
<td>0.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Since being first introduced, the Drucker-Prager plasticity model (Drucker and Prager, 1952) has been continuously modified and expanded over the years. A typical Drucker-Prager Cap model (ABAQUS, 2013) is used in the current analysis. This is an incremental plasticity model based on the existence of a yield surface and a flow potential. The model is assumed to be isotropic and its yield surface is described, in the deviatoric stress plane, by three segments: a shear failure surface $F_s$, providing dominantly shearing flow, a “cap” $F_c$, providing an inelastic hardening mechanism for plastic compaction, and a transition region $F_t$ between the first two segments, meant to provide a smooth surface (facilitating only the model’s numerical implementation). Each of the yield surfaces is uniquely defined with the help of six parameters: $\beta$, $d$, $p_0$, $R$, $p_b$ and $\alpha$. The friction angle, $\beta$ and the cohesion, $d$ are required for defining the Drucker-Prager shear failure surface; the cap eccentricity, $R$ and the evolution parameter, $p_0$ are required to define the cap surface, and the hydrostatic compression yield stress $p_b$ as a function of the volumetric plastic strain is required to define the cap hardening/softening law, while the transition surface is defined by $\alpha$. For more detailed information one may refer to special literature in field (e.g. Drucker and Prager, 1952 and ABAQUS, 2013).

Hence, a plane strain model with the dimensions of $6.5\text{m} \times 15\text{m}$, consisting of 4 node bilinear elements, as depicted by Figure 1. In the contact region fine elements in the size of 20mm were allocated, while mesh coarseness increases up to 185mm at the lower boundary of the FE model. The coarser elements positioned at larger distances from the contact surface do not play an important role in the FEM simulation, thus their dimensions could have been increased, maintaining at the same time, the accuracy of the results.
4 RESULTS OF THE ANALYSIS

Hereinafter the results of the numerical analysis conducted according to the above mentioned theoretical issues are presented. The research comprised the analysis of all the above mentioned construction stages and the manner in which they influence the final results. However, for the purpose of this paper only the effects of the constitutive model on the compacted soil simulation and the processes happening at the interface with the roller are presented.

Figure 3. Results of the numerical modelling

Figure 3 is intended for qualitatively describing the effects of the compacted material after the roller has been propelled for about $9s$ (approx. $7.8m$ from its starting position). The plastic volumetric strain resulted during the compaction are accounted for as a qualitative measure of the process. Negative inelastic volumetric strains ($-\varepsilon_{p^\text{vol}}$) indicating soil compaction are depicted by Figure 3a. Their distribution is strongly related to the hydrostatic compression yield stress ($P_b$, presented in Figure 3c), through the hardening/softening law provided by the cap surface of the constitutive model. The cap helps also controlling the inelastic volume increase (depicted by the plastic positive volumetric strains $+\varepsilon_{p^\text{vol}}$ in the middle part of Figure 3b), which extends, on both sides of the oscillatory drum, for a depth of about 5cm from the soil surface. This indicates the dilation of the soil as it yields on the Drucker-Prager shear surface and on the transition yield surface. Hence, this denotes a softening of the soil marking a drawback of the constitutive model used in the simulation of dynamic soil compaction process.

Furthermore, the distribution of the equivalent plastic strains for Drucker-Prager failure surface are presented in Figure 3d, together with the equivalent plastic strains for the cap surface in Figure 3e and the equivalent plastic strains for the transition surface (Figure 3f). Thus, it emphasizes that the soil compaction by oscillatory roller is mainly achieved through plastic strains and a linear elastic constitutive soil model cannot be effective in simulating these effects.

Meant as a wear indicator for the drum’s metallic surface, the slip energy is depicted by Figure 4. It represents the scalar product between the contact shear force (whose variation in time is presented in the top part of the Figure 4) and the slip velocity (middle part of Figure 4) developed through the frictional contact between the oscillatory drum and the soil. For each of the period, the slip energy reaches its maximum while the drum slips in the direction opposite to its propelling, due to a larger contact length.
5 CONCLUSIONS

The current paper presents the numerical modelling of a dynamic roller-soil interaction in the case of soil compaction with oscillatory rollers. The theoretical concepts that underlie the conceiving of the 2D plane strain model are issued. To this end, the modelling of the oscillatory drum and the simulation of roller frame actions and its effects on it are presented. Notions regarding dynamically loaded soil modelling are briefly stated and modified Drucker-Prager Cap model is employed for soil compaction simulation. Results of the conducted numerical analysis are presented through the inelastic soil volume changes related to the stresses induced during oscillatory compaction. By comparing this to the effects observed during real soil compaction some uncertainties arise. This is related to parts of soil dilating due to shearing during the compaction process, instead of an expected volume reduction as observed in reality. However, considering the outcome of the numerical modelling related to the inelastic volumetric strains as a qualitative measure of dynamic soil compaction, places the numerical analysis results on the verisimilitude side. Based on the shear stresses and relative slip velocities developed at the contact area between the soil and the oscillatory drum, the energy lost between the two bodies in contact is estimated. Furthermore, the conceived numerical model and the results presented in the current paper serve as solid basis for further developments and analysis related to oscillatory soil compaction and drum wear estimation.

REFERENCES

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