Numerical Modelling of Rayleigh Wave Propagation in Course of Rapid Impulse Compaction

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Abstract. As the soil improvement technologies are the area of a rapid development, they require designing and implementing novel methods of control and calibration in order to ensure the safety of geotechnical works. At Wroclaw University of Science and Technology (Poland), these new methods are continually developed with the aim to provide the appropriate tools for the preliminary design of work process, as well as for the further ongoing on-site control of geotechnical works (steel sheet piling, pile driving or soil improvement technologies). The studies include preliminary numerical simulations and field tests concerning measurements and continuous histogram recording of shocks and vibrations and its ground-born dynamic impact on engineering structures. The impact of vibrations on reinforced concrete and masonry structures in the close proximity of the construction site may be destroying in both architectural and structural meaning. Those limits are juxtaposed in codes of practice, but always need an individual judgment. The results and observations make it possible to delineate specific modifications to the parameters of technology applied (e.g. hammer drop height). On the basis of numerous case studies of practical applications, already summarized and published, we were able to formulate the guidelines for work on the aforementioned sites. This work presents specific aspects of the active design (calibration of building site numerical model) by means of technology calibration, using the investigation of the impact of vibrations that occur during the Impulse Compaction on adjacent structures. A case study entails the impact of construction works on Rayleigh wave propagation in the zone of 100 m (radius) around the Compactor.

1. Introduction

Construction activities, road and railway traffic, and operation of machines form the four categories in the classification of human activities which can generate ground vibrations according to Athanasopoulos and Pelekis [1], Bachmann and Ammann [2]. This paper takes a special interest in the first of the factors enumerated above. Srbulov [3] stated that the main construction or demolition activities causing dynamic problems in close proximity of structures are caused by pile or sheet pile driving and dynamic soil compaction; as well as by demolition of structures, rock excavation and soil deep compaction by explosives.

The paper describes the results of a Rapid Impulse Compaction (RIC) simulation. RIC is a soil compaction technology, widely used for non-cohesive soils and debris fills (Figure 1).
The safety measures needed to prevent structures from damage have been described by various standards, and they give particular vibration criteria depending on various technologies and construction materials. These numerous approaches in this area have been recently compared and summarized by Athanasopoulos and Pelekis [1], Brzakala et al. [4], Hwang [5], Pieczynska and Rybak [6], Rybak and Tamrazyan [7], Skipp [8], Brzakala and Baca [9], Oliveira and Fernandes [10] or Srbulov [3]. The reduction of ground vibrations was in the scope of interest of Herbut [11,12,13], who proposed specialized method of minimizing them with the use of an active generator.

Numerical methods are the most frequently used tool in solving the wave propagation problem (especially these, which at the same time satisfy the radiation condition in infinity, such as Finite Element Method in connection with non-reflecting boundaries or Boundary Element Method). In this work, FEM (Finite Element Method) is implemented in order to address the problem of wave propagation in non-homogeneous ground conditions when load is applied on the soil surface.

2. Equations of motion for a transversally isotropic medium with hysteretic damping

Let us consider stresses acting on a soil element with side measurements $dx, dy, dz$. The sum of the forces acting in the $x$-, $y$- and $z$-directions, including damping forces, gives the differential equations (1) of motion for the soil medium

\[
\begin{align*}
\sum P_x &= 0: \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + tr \cdot \frac{\partial \sigma_x}{\partial t} + tr \cdot \frac{\partial \tau_{yx}}{\partial t} + tr \cdot \frac{\partial \tau_{xz}}{\partial t} = \rho \frac{\partial^2 u}{\partial t^2}, \\
\sum P_y &= 0: \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial z} + tr \cdot \frac{\partial \tau_{yx}}{\partial t} + tr \cdot \frac{\partial \sigma_y}{\partial t} + tr \cdot \frac{\partial \tau_{xy}}{\partial t} = \rho \frac{\partial^2 v}{\partial t^2}, \\
\sum P_z &= 0: \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{yz}}{\partial y} + tr \cdot \frac{\partial \tau_{sz}}{\partial t} + tr \cdot \frac{\partial \sigma_z}{\partial t} + tr \cdot \frac{\partial \tau_{yz}}{\partial t} = \rho \frac{\partial^2 w}{\partial t^2}
\end{align*}
\]

where $u$, $v$ and $w$ are the displacement components in the $x$-, $y$- and $z$-directions, respectively; $\rho$ is the soil density; $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$ are normal and shear elastic stresses, respectively; and $tr$ is the relaxation time, which is inversely proportional to the excitation frequency $tr = 2\xi/\omega$. The relations for strains in terms of displacements are assumed as: $\varepsilon_x = \partial u / \partial x$, $\varepsilon_y = \partial v / \partial y$, $\varepsilon_z = \partial w / \partial z$, $\gamma_{xy} = \partial v / \partial x + \partial u / \partial y$, $\gamma_{xz} = \partial w / \partial x + \partial u / \partial z$, $\gamma_{yz} = \partial w / \partial y + \partial v / \partial z$. For an elastic transversally isotropic material with a horizontal plane of isotropy, the elastic strain stress relationship can be presented in the following form (2):
where \( C_{11} = 1/E_x \), \( C_{12} = -v_x/E_x \), \( C_{13} = -v_y/E_y \), \( C_{33} = 1/E_z \), \( C_{55} = 1/G_{xz} \), and \( C_{66} = 2(1 + v_x)/E_x \). \( E_x, E_y = E_x \) are the Young’s moduli in the x- and y-directions, respectively, in the plane of isotropy. \( E_z \) is the Young’s modulus in the z-direction, in the plane perpendicular to the plane of isotropy. Similarly \( v_x, v_y = v_x \) and \( v_z \) are the Poisson ratios in the plane of isotropy and in the plane perpendicular to the plane of isotropy, respectively. \( G_{xz} \) is the shear modulus in the plane perpendicular to the plane of isotropy.

### 3. Finite element model

Similar to Lysmer and Kuhlemeyer [14], the authors assumed absorbing viscous boundary conditions to avoid wave reflection at the boundary. Instead of analysing coupled impulse series, the load can be subject to scrutiny as just one impulse due to the high wave velocity and low excitation frequency. Each of the impulses does not influence the other. These circumstances are the same as on the actual on-site conditions during the Rapid Impulse Compaction.

The vibration source in the form of impulse pressure \( P(t) \) in Figure 2 is located in the middle of the considered region \((x=125 \text{ m}, y=125 \text{ m}, z=0)\). It is applied to a circle region with a diameter of 1.5 m. The dynamic compaction energy is assumed as \( E=180 \text{ kNm} \). To calculate the pressure applied to the ground surface the ground displacement direct below the hammer is assumed as 2.5 cm. According to these assumptions pressure applied to the ground surface is equal to \( A=4.15 \text{ MPa} \). The excitation force can be described by the following formula: \( P(t) = A \cdot \left( H(t - t_b) - H(t - t_e) \right) \), where \( H(t) \) is the Heaviside function, \( t_b \) is the time when the pressure is applied to the ground surface, \( t_e \) is the time when the hammer goes up. For the analysed example, \( t_b = 0 \), \( t_e = 0.05 \text{ s} \). Figure 2 shows the assumed transversally isotropic, layered half space.
We consider two cases: the first one – before the soil compaction and the second one, after the soil properties improvement. It is assumed that due to dynamic compaction the soil properties between the ground surface and the depth of 5 m are 20 percent better than before. For the first considered case only one ground layer is assumed. The soil characteristics are as follows: shear modulus $G_{xz,1} = 80 \text{ MPa}$; Young’s modulus in the plane of isotropy $E_{x,1} = 3.865G_{xz,1}$; Young’s modulus in the plane perpendicular to the plane of isotropy $E_{z,1} = 2.863G_{xz,1}$; Poisson’s ratios: $\nu_{x,1} = 0.280$ and $\nu_{z,1} = 0.165$; mass density of the soil $\rho_1 = 2000 \text{ kg/m}^3$ and damping coefficient $\xi = 1\%$. For the second case two different dynamic soil parameters are taken into account (Figure 2). For the shallow deposit, the dynamic soil parameters are as follows: shear modulus $G_{xz,1} = 96 \text{ MPa}$; Young’s modulus in the plane of isotropy $E_{x,1} = 3.865G_{xz,1}$; Young’s modulus in the plane perpendicular to the plane of isotropy $E_{z,1} = 2.863G_{xz,1}$; Poisson’s ratios: $\nu_{x,1} = 0.280$ and $\nu_{z,1} = 0.165$; mass density of the soil $\rho_1 = 2000 \text{ kg/m}^3$ and damping coefficient $\xi = 1\%$. The boundary surface between the first and second layers is horizontal. It is located on the depth of 5 m, like the influence depth of dynamic compaction. For the second layer, the dynamic soil parameters are as follows: shear modulus $G_{xz,2} = 80 \text{ MPa}$; Young’s moduli: $E_{x,2} = 3.865G_{xz,2}$ and $E_{y,2} = 2.863G_{xz,2}$; Poisson’s ratios: $\nu_{x,2} = 0.301$ and $\nu_{y,2} = 0.182$; damping coefficient $\xi = 1\%$; and mass density of the soil $\rho_2 = 2000 \text{ kg/m}^3$. FlexPDE Professional Version 5.0.7. software based on Finite Element Method was applied for solving the presented partial differential equations with the corresponding absorbing boundary conditions. The further assumptions were: a fully bonded soil foundation interface, and four-noded linear tetrahedron finite elements with three degrees of freedom at each node. The time of analysis is equal to $T=1\text{s}$, and the analysed system consist of 39389 nodes and 236334 unknowns.

![Figure 3. Vertical displacements due to impulse compaction in the middle of the considered region for $y=125\text{m} \ t=0.46T$](image-url)
4. Results and conclusions

In the technology of Rapid Impulse Compaction in the form of an impulse load, the Raleigh Wave is produced – a wave which propagates the source of vibration outwards. Additionally, new body waves appear. The incompressible soil layer reflects the new body wave, which reaches the ground surface and becomes the source of the new surface wave. This phenomenon is repeated but with the less energy (Figure 3).

Similarly to the experimental results maximum observed velocities amplitudes in both directions – horizontal and vertical are presented for the points located in the distance of 3.3 m, 6.7 m, 10 m, 13.3 m, 16.7 m, 20 m, 30 m, 50 m, 75 m, 100 m on the right side of the applied load. New $x'$ coordinate is introduced in Figure 2 ($x' = 0$ is in the middle of the region, where the load is applied to the ground surface).

The results of numerical analyses of two cases, before and after dynamic compaction, are shown in Figures 4-5; the state before the dynamic compaction has been marked with blue dots, whereas the state after the compaction completion – with red dots.

![Figure 4. Attenuation of velocity amplitudes in vertical direction](image)

![Figure 5. Attenuation of velocity amplitudes in horizontal direction](image)

Both, the shape of the attenuation function and the values of peak particle velocities are very similar to the results of field measurements reported by Pieczyńska and Rybak [6] and Papan et al. [15]. In the reported case, the research served to give recommendations for a contractor in order not to approach closer than 35-40 meters to the neighbouring residential houses.

The conformity of results from the Finite Element Model and a real test prove the possibility of making a dynamic analysis (based on ground survey and previously measured machine impact) prior to the start of geotechnical works, and thus add corrections to proposed technology. Fortunately, modern impact hammers make it possible to change the hammer drop height for some part or the whole duration of the works. Such an attitude may prevent investors and construction companies from claims of damages. It must be however remembered, that the “switching” of the hammer may limit the efficiency
of soil compaction (depth) and prolong the time of works. In other case, when the necessary precautions impose the works to come to a standstill, the investment costs increase. That often results from the passive attitude on the part of investors and contractors.

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