The surface wave attenuation as the effect of vibratory compaction of building embankments

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Abstract. There are two different sources of dynamic effects observed on buildings and structures – natural phenomena and human activities. Both may be related to the mining production or civil engineering construction. Ground vibrations induced by human activities characterize much lower intensity compared to the natural phenomena like earthquakes. However, due to the high urban development and sustainable development ideas, preventing the destructive effect of man-made vibrations belongs to the most important problems considering the structure and soil dynamics. Construction activities, road and railway traffic, and operation of machines, including crushing of spoil material (debris) from demolition works are the main categories in the classification of human activities which can generate ground vibrations. This paper takes a special interest in the first of the factors mentioned above. It is evident 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 by means of vibratory rollers or impulse compactors; as well as by demolition of structures, rock excavation and soil deep compaction by explosives. The vibration monitoring process needed to prevent structures from damage is described by various standards. They give particular criteria depending on various technologies and construction materials. The reduction of man-made ground vibrations is now the crucial scope of interest due to the need for sustainable technologies implementation. The negative environmental impact may be reduced at the source. Some new specialized methods are also proposed for minimizing the vibration transmission with the use of an active generator. The aim of the presented paper is to describe the modelling of dynamic vibratory soil compaction, using finite element method. The presented solution is addressed to short time vibration, generated by geotechnical works. This conclusion can be helpful by panning geotechnical works in the neighbourhood of vibration sensitive buildings/structures.

1. Introduction
There are many categories in the classification of human activities which can generate ground vibrations [1-3]. Srbulov stated that the main construction or demolition activities causing dynamic problems in neighbouring structures are caused by pile or sheet pile driving and dynamic soil compaction [4]. The vibration monitoring process needed to prevent structures from damage is described by various standards. They give particular criteria depending on various technologies and construction materials.
The reduction of man-made ground vibrations was in the scope of interest of Herbut [18-20], who proposed a specialized method of minimizing them with the use of an active generator. The presented solution is addressed to short time vibration, generated by geotechnical works. The aim of the presented paper is to describe the modelling of dynamic vibratory soil compaction, using finite element method.

Numerical methods are nowadays the most popular tool used in solving the problem of wave propagation in soil. The most common are Finite Element Method in connection with non-reflecting boundaries or Boundary Element Method which at the same time satisfy the radiation condition in infinity. In the presented paper FEM (Finite Element Method) is implemented in order to address the problem of wave propagation in non-homogeneous ground conditions. Harmonic force is applied to the ground surface to describe load generated by vibratory roller during soil improvement (figure 1). The question is, how the soil compaction influences the Rayleigh wave propagation? The answer to this question could be helpful during planning geotechnical works in the vicinity of existing structures. The similar problem, but in the case of impulse dynamic soil compaction was presented by Herbut and Rybak [14].

![Figure 1. Dynamic compaction by the use of a vibratory roller](image)

2. Equation of motion for a transversally isotropic damped medium

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 where $u$, $v$ and $w$ are the displacement components in the $x$-, $y$- and $z$-directions, respectively; $\rho$ is the soil density; $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{yx} = \tau_{yx}$, $\tau_{xz} = \tau_{xz}$, $\tau_{yz} = \tau_{zy}$ are normal and shear elastic stresses, respectively; and $t_r$ is the relaxation time, which is inversely proportional to the excitation frequency $\omega$.

\[
\sum P_x = 0: \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + t_r \cdot \frac{\partial \sigma_x}{\partial t} + t_r \cdot \frac{\partial \tau_{yx}}{\partial t} + t_r \cdot \frac{\partial \tau_{zx}}{\partial t} = \rho \frac{\partial^2 u}{\partial t^2}
\]

\[
\sum P_y = 0: \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + t_r \cdot \frac{\partial \sigma_y}{\partial t} + t_r \cdot \frac{\partial \tau_{xy}}{\partial t} + t_r \cdot \frac{\partial \tau_{zy}}{\partial t} = \rho \frac{\partial^2 v}{\partial t^2}
\]

\[
\sum P_z = 0: \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + t_r \cdot \frac{\partial \tau_{xz}}{\partial t} + t_r \cdot \frac{\partial \tau_{yz}}{\partial t} + t_r \cdot \frac{\partial \sigma_z}{\partial t} = \rho \frac{\partial^2 w}{\partial t^2}
\]
The relations for strains in terms of displacements are assumed in the following form: 
\[ \varepsilon_x = \frac{\partial u}{\partial x}, \]
\[ \varepsilon_y = \frac{\partial v}{\partial y}, \]
\[ \varepsilon_z = \frac{\partial w}{\partial z}, \]
\[ \gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}, \]
\[ \gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}, \]
\[ \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}. \]
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):

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{yz} \\
\gamma_{xz} \\
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{55} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66} \\
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yz} \\
\tau_{xz} \\
\tau_{xy} \\
\end{bmatrix},
\]

where \( C_{11} = 1/E_x, \) \( C_{12} = -v_x/E_x, \) \( C_{13} = -v_z/E_z, \) \( C_{33} = 1/E_z, \) \( C_{55} = 1/G_{xz}, \) and \( C_{66} = 2(1 + v_x)/E_x. \) \( E_x, E_y = E_x, \) are the Young’s moduli in the two horizontal directions, in the plane of isotropy. \( E_z \) is the Young’s modulus in the plane perpendicular to the plane of isotropy, in the vertical direction. 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. Site measurements

All the control procedures presented for the purpose of the current study were performed during the training period of Cheynesh Kongar-Syuryun at Wrocław University of Science and Technology. The building site was located near Kłodzko (Poland). The results of vibration velocities were measured at the distance from 5m to 20m from the source of vibrations (the roller) as presented in figure 2.

**Figure 2.** Vibration control in course of soil compaction

The tests were performed in June 2019 at the building site, where large amounts of debris and crushed local rocks will be used. The methodology of control was based on the recording of frequencies and vibration velocities. The “working” frequency during soil compacting works oscillated around 27Hz, which is a typical range (value) for vibratory rollers. The maximum value of vibration velocity by means of Peak Particle Velocity PPV reached around 12 mm/s when the roller approached at the distance of app. 5 m from the accelerometer. A closer operation was technically possible but the distance was set for safety reason. It is important to underline that using crushed stone (figure 3) or using more than one source of vibration at the same time (figure 4) may seriously affect the above mentioned range of measured values.
4. Finite element model

Similar to Lysmer and Kuhlemeyer [21], the authors proposed absorbing boundary conditions to avoid wave reflection at the boundary. The harmonic load is assumed to model dynamic compaction caused by vibratory roller STAVOSTROJ VV 1500D. According to the technical specification – excitation frequency is about 29 Hz -35 Hz and centrifugal force 324 kN – 237 kN. The following data were assumed during calculations: excitation force 324 kN, excitation frequency 29 Hz.

The vibration source in the form of harmonic pressure \( P(t) \) in Figure 5) is located in the middle of the considered region. It is applied to a rectangle region with diameters of 0.3 m, 3 m. The excitation force can be described by the following formula: \( P(t) = A \sin(\omega t) \). Figure 2 shows the assumed transversally isotropic, layered half space. Two different cases are taken into account: the first one – before the soil compaction and the second one – after the improvement of soil properties of the first layer (Figure 5). It is assumed that due to dynamic compaction the soil properties between the ground surface and the depth of 2 m are 20 per cent better than before. For the first considered case, only one ground layer is assumed. The soil parameters are as follows: shear modulus \( G_{xz,1} = 80 \) MPa; Young’s modulus in the plane of isotropy \( E_{xz,1} = 3.865G_{xz,1} \), Young’s modulus in the plane perpendicular to the
plane of isotropy $E_{x,1}=2.863 G_{xz,1}$; Poisson’s ratios: $\nu_{x,1}=0.280$ and $\nu_{z,1}=0.165$; mass density of the soil $\rho=2000$ kg/m$^3$ and damping coefficient $\xi=1\%$.

For the second case (after soil improvement) two different dynamic soil parameters are taken into account (figure 5). For the shallow deposit, the dynamic soil parameters are as follows: shear modulus $G_{xz,1}=96$ MPa; Young’s modulus in the plane of isotropy $E_{x,1}=3.865 G_{xz,1}$, Young’s modulus in the plane perpendicular to the plane of isotropy $E_{z,1}=2.863 G_{xz,1}$; Poisson’s ratios: $\nu_{x,1}=0.280$ and $\nu_{z,1}=0.165$; mass density of the soil $\rho=2000$ 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 2 m, like the influence depth of vibratory roller. For the second layer, the dynamic soil parameters are as follows: shear modulus $G_{xz,2}=80$ MPa; $E_{x,2}=3.865 G_{xz,2}$, Young’s modulus in the plane perpendicular to the plane of isotropy $E_{z,2}=2.863 G_{xz,2}$; Poisson’s ratios: $\nu_{x,2}=0.280$ and $\nu_{z,2}=0.165$; mass density of the soil $\rho=2000$ kg/m$^3$ and damping coefficient $\xi=1\%$. FlexPDE Professional Version 5.0.7. software based on Finite Element Method was applied for solving the 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 $10T$, where $T$ is the period of harmonic excitation. The analysed system consists of 39184 nodes and 235104 unknowns.

5. Results and discussions

In figure 6, vertical displacements of the soil medium are presented due to dynamic compaction. The results are presented for the cross-section in the middle of the analysed region, along the red line in Figure 5. It can be observed that due to harmonic excitation applied to the ground surface in the middle of the presented region, two types of waves are generated. The most significant is the Rayleigh wave, which propagates near the ground surface, source of vibration outwards (figure 6, figure 7). Additionally, body waves (P-wave, S-wave) appear. They propagate from the ground surface deeper in the ground. Body wave can be observed in figure 3, as a blue rectangle in the bottom part of the analysed region.
In figure 8 maximum absolute value of the velocity in the vertical direction is presented for 10 selected points on the right site of the applied load (along the red line in figure 8). Very similar results were presented by Papan in work [22]. As values for horizontal directions x and y were much smaller than those for the vertical one, the results for horizontal components are omitted in the presented investigations. The distance between measure points (blue and red dots in figure 8) is 2 m. Blue dots relate to the situation before soil compaction and red dots after it. It can be observed that soil improvement even on the shallow depth (2 m), reduces the dynamic response of a soil medium. In the presented case, when the elastic moduli of the first layer are improved by about 20 per cent, the level of velocity reduction is about 15 per cent.

**Figure 6.** Vertical displacements (in z-direction), 0.5 m below the ground surface

**Figure 7.** Vertical displacements (in z-direction) during harmonic excitation in the middle of the analyzed region, for t=0.072s, for increased values of elastic constants of the first layer
Figure 8. The maximum value of the observed velocity in the vertical direction; red dots – after soil compaction, blue dots – before soil compaction

Figure 9. Values of the observed velocities in the time domain in the course of soil compaction

One may observe that the maximum values of Peak Particle Velocity (PPV) observed at the building site (figure 9) are similar to the values derived from numerical analysis (figure 8) in corresponding conditions.

6. Conclusions
The presented results can be helpful for planning of geotechnical works in the neighbourhood of vibration sensitive buildings/structures. The results of similar investigations, but for impulse, dynamic compaction were recently presented by Herbut and Rybak [14]. The results are highly dependent on the ground conditions and vibration energy at the source. The importance of such examination is confirmed by works of Wojtowicz et al [23,24] where the authors refer to the problem of soil set in the close vicinity of geotechnical works. The necessity of further examination and juxtaposing of the results in the databases is recommended as the final conclusion of the presented study.

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