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NUMERICAL INVESTIGATIONS ON VIBRATING MOTION WITH INERTIAL LOAD OF VIBRATORY PILE HAMMER STIFFLY COUPLED WITH EXCAVATOR

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Abstract

A vibratory pile hammer (VPH) is a mechanical device used to drive steel piles as well as tube piles into soil to provide foundation support for buildings or other structures. In order to increase the stability and the efficiency of the VPH work in the over-resonance frequency, a new VPH construction was developed in the Military University of Technology. The new VPH contains a system of counter-rotating eccentric weights, powered by hydraulic motors, and designed in such a way that horizontal vibrations cancel out, while vertical vibrations are transmitted into the pile. This system is suspended in the static parts by the adaptive variable stiffness pillows based on a smart material, magnetorheological elastomer (MRE), which rheological and mechanical properties can be reversibly and rapidly controlled by an external magnetic field. The work presented in the paper is a part of the modified VPH construction design process. It concerns the development of the numerical model of the VPH and soil interaction that will describe resonance conditions, resonance frequencies with consideration of soil susceptibility, coupling phenomenon and elastomer changeable stiffness. On the base of developed theoretical equations, the frequency of VPH piling will be regulated to assure the over-resonance work.

Keywords: *elastomer, vibrations, simulation, resonance, numerical analysis*

1. Introduction

A vibratory pile hammer (VPH) is a mechanical device used to drive steel piles as well as tube piles into soil to provide foundation support for buildings or other structures. In order to increase the stability and the efficiency of the VPH work in the over-resonance frequency, a new VPH construction was developed in the Military University of Technology. The new VPH contains a system of counter-rotating eccentric weights, powered by hydraulic motors, and designed in such a way that horizontal vibrations cancel out, while vertical vibrations are transmitted into the pile. This system is suspended in the static parts by the adaptive variable stiffness pillows based on a smart material, magnetorheological elastomer (MRE), which, rheological and mechanical, properties can be reversibly and rapidly controlled by an external magnetic field [1]. The inside construction of VPH with the elastomer pillows is shown in Fig. 1.

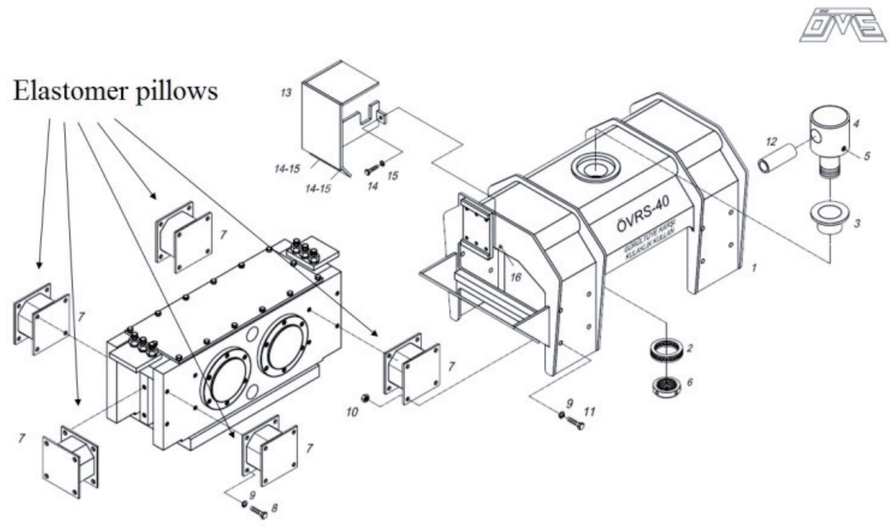

Fig. 1. Inside construction of VPH with elastomer pillows

Magnetorheological elastomers (MREs) belong to the group of so-called smart materials, which respond to an external stimulus by changing their viscoelastic properties. They are the solid analogues of magnetorheological fluids (MRFs), consisting of magnetically permeable particles (such as iron) added to a viscoelastic polymeric material prior to crosslinking [2, 3]. Before the curing process of the polymer, a strong external magnetic field is applied. The field induces dipole moments within the particles, which seek minimum energy states. The chains of particles with collinear dipole moments are formed and curing of the polymeric matrix material locks the chains in place. In this orientation, the particles can form separate chains in the three-dimensional simple lattice structures or even more complicated structures, where particles have multiple interaction points [1, 3]. The microstructure of the MRE cured under the magnetic field is presented in Fig. 2.

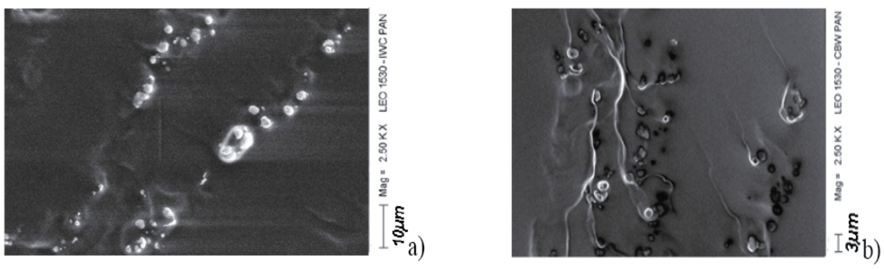

Fig. 2. SEM images of MRE obtained from PU 80/20 filled with 11.5 vol. % of carbonyl-iron particles, cured under magnetic field of a) 100 mT, b) 300 mT [2]

The work presented in the paper is a part of the modified VPH construction design process. It concerns the development of the numerical model of the VPH and soil interaction that will describe resonance conditions, resonance frequencies with consideration of soil susceptibility, coupling phenomenon and elastomer changeable stiffness. On the base of developed theoretical equations, the frequency of VPH piling will be regulated to assure the over-resonance work.

2. VPH equations of motion

The equations of movement of the analysed VPH can be assumed on the base of the vibration theory and vibro-isolation literature review, especially [4-7]. The basic case, when the VPH is hanged stiffly on the excavator, is presented in Fig. 3 and can be described with the following equation:

$$(m+m_p)\ddot{x}+f(\dot{x},x)=G-P(t)+A\omega^2\sin\omega t\,, \tag{1}$$

where:
m – dynamic mass of VPH (720 kg),
m_p – mass of the pile (kg),
$f(\dot{x},x)$ – nonlinear function describing stiffness and damping in the elastomer elements,
G – gravity $G=(m+m_p)g$,
$P(t)$ – periodical function describing the pile vs. soil resistance (friction and shearing),
A – centrifugal force amplitude (275 kN),
ω – frequency of centrifugal load $\omega = \frac{\pi n}{30} = 262 \frac{1}{s}$ ·

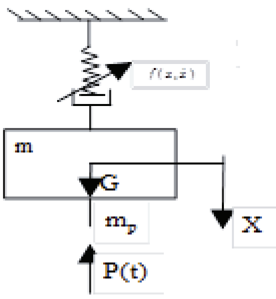

Fig. 3. Scheme of the VPH hanged stiffly on the excavator

In the first assumption for the frequencies calculations the linear functions can be considered, what results with the equation:

$$(m+m_p)\ddot{x}+c\dot{x}+kx = G-P(t)+A\omega^2 \sin \omega t\,, \tag{2}$$

where:
c – damping coefficient,
k – elasticity constant.

The natural frequency can be calculated with the equation:

$$\omega_0^{\;2} = \frac{k}{m+m_p} \cdot \tag{3}$$

In this simplified case the following linear functions are applied:

$$m_1\ddot{x}_1 - c(\dot{x}-\dot{x}_1) - k(x-x_1) = G_1\,, \tag{4a}$$

$$(m+m_p)\ddot{x}+c(\dot{x}-\dot{x}_1)+k(x-x_1) = G-P(t)+A\omega^2 \sin\omega t\,. \tag{4b}$$

When calculating resonance frequency, the damping and load can be omitted and considering the harmonic solution, the condition of determinant zeroing can be applied:

$$\begin{vmatrix} k_1 - m_1\omega_0^{\;2} & -k \\ -k & k - m\omega_0^{\;2} \end{vmatrix} = 0\,. \tag{5}$$

For the function f (Eq. 1) description well known hyper elastic materials theory models can be used. Mooney-Rivlin, Ogden and Yeoh material models are most often applied [8].
The hyper elastic materials theory application plays the key role in analysed VPH motion description. This theory considers the relative extension is considered, which for small deformations is coupled with classic deformation theory with the equation:

$$\lambda_i = \varepsilon_i + 1\,. \tag{6}$$

Volume is calculated as:

$$J = \lambda_1 \lambda_2 \lambda_3 \tag{7}$$

and its change as:

$$\Delta J = J - 1 . \tag{8}$$

Previous research [8] showed that for the description of elastomer properties the polynomial model is the best to use, in the general form:

$$W = \sum_{i+j=1}^{N} c_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{d_k} (J-1)^{2k} , \tag{9}$$

where:
W – elastic energy function,
c_{ij} – material constants,
d – material compressibility parameter,
$\bar{I}_1, \bar{I}_2$ – invariants of the deviatoric part of deformations tensor given by:

$$\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2 ,$$

$$\bar{I}_2 = \bar{\lambda}_1^2 \bar{\lambda}_2^2 + \bar{\lambda}_2^2 \bar{\lambda}_3^2 + \bar{\lambda}_3^2 \bar{\lambda}_1^2 . \tag{10}$$

The first component of the sum (9) describes the characteristic deformations, the second one – volume deformations. The polymers are often considered as incompressible and the volume deformations component can be omitted.

The polynomial models were developed many years ago. The first model was the Neo-Hookean one, calculated as:

$$W = \frac{\mu}{2} (\bar{I}_1 - 3) + \frac{1}{d} (J-1)^2 . \tag{11}$$

The next model was Mooney one, developed in 1949:

$$W = C_1 (\bar{I}_1 - 3) + C_2 (\bar{I}_2 - 3) \tag{12}$$

and Mooney-Rivlin model:

$$W = c_{10} (\bar{I}_1 - 3) + c_{01} (\bar{I}_2 - 3) , \tag{13}$$

then broaden with the component that considers the compressibility:

$$W = c_{10} (\bar{I}_1 - 3) + c_{01} (\bar{I}_2 - 3) + \frac{1}{d} (J-1)^2 . \tag{14}$$

Then the three parametric Mooney-Rivlin model was described as:

$$W = c_{10} (\bar{I}_1 - 3) + c_{01} (\bar{I}_2 - 3) + c_{11} (\bar{I}_1 - 3)(\bar{I}_2 - 3) + \frac{1}{d} (J-1)^2 , \tag{15}$$

five parametric Mooney-Rivlin model:

$$W = c_{10} (\bar{I}_1 - 3) + c_{01} (\bar{I}_2 - 3) + c_{20} (\bar{I}_1 - 3)^2 + c_{02} (\bar{I}_1 - 3)^2 + c_{11} (\bar{I}_1 - 3)(\bar{I}_2 - 3) + \frac{1}{d} (J-1)^2 \tag{16}$$

and nine parametric Mooney-Rivlin model:

$$\begin{aligned} W = {} & c_{10} (\bar{I}_1 - 3) + c_{01} (\bar{I}_2 - 3) + c_{20} (\bar{I}_1 - 3)^2 + c_{02} (\bar{I}_2 - 3)^2 + c_{30} (\bar{I}_2 - 3)^3 + c_{03} (\bar{I}_2 - 3)^3 \\ & + c_{11} (\bar{I}_1 - 3)(\bar{I}_2 - 3) + c_{21} (\bar{I}_1 - 3)^2 (\bar{I}_2 - 3) + c_{12} (\bar{I}_1 - 3)(\bar{I}_2 - 3)^2 + \frac{1}{d} (J-1)^2 . \end{aligned} \tag{17}$$

The reduced polynomial model [9] is often used in practice and is calculated as:

$$W = \sum_{i=1}^{N} c_i (\overline{I}_1 - 3)^i + \sum_{k=1}^{N} \frac{1}{d_k} (J-1)^{2k} . \tag{18}$$

The second component of the sum was omitted.

In Finite Element Method only the models up to six parameters are used, the higher ones are generating the numerical instability.

Firstly, the elastomer element of VPH was described with the first component assuming the incompressibility as:

$$W = C_1 (I_1 - 3). \tag{19}$$

Using the incompressibility condition:

$$\lambda_1^2 \lambda_2^2 \lambda_3^2 = 1 , \tag{20}$$

we get:

$$\lambda_2^2 = \frac{1}{\lambda_1} ; \lambda_3^2 = \frac{1}{\lambda_1} \cdot \tag{21}$$

Putting (21) to (19) we can get:

$$W = C_1 \left(\lambda_1^2 + \frac{2}{\lambda_1} - 3 \right). \tag{22}$$

After differentiating in accordance to:

$$\sigma_1 = \frac{\vartheta W}{\vartheta \lambda_1} \tag{23}$$

and including the coordination x as:

$$\lambda_1 = \frac{x + l}{l} , \tag{24}$$

where l is a length of elastic element, the equation for elastic force is given as:

$$F = k \left[x + l - \frac{l^3}{(x+l)^2} \right] \cdot \tag{25}$$

Where elastic coefficient $k = \frac{2C_1}{l}$. Putting Eq. (20) to Eq. (1) the basic equation for VPH motion is as follows:

$$(m + m_p)\ddot{x} + c\dot{x} + k \left[x + l - \frac{l^3}{(x+l)^2} \right] = G - P(t) + A\omega^2 \sin \omega t , \tag{26}$$

where $c\dot{x}$ is a linear viscose damping in elastomer elements.

3. Numerical analyses

The numerical analysis of the vibrating motion of with the inertial load of the VPH working on the stiff coupling with the excavator was carried out on the base of equations presented above.

The natural frequency was:

$$\omega_0^2 = \frac{k}{m} = \frac{400000}{1000} = 400\frac{1}{s^2}; \omega = 20\frac{1}{s}.$$

The non-dimensional damping was calculated as follows:

$$2h = \frac{c}{m} = 1; \gamma = \frac{h}{\omega} = \frac{0.5}{20} = 0.025.$$

The amplitude of load for the maximum values was:

$$A = \frac{A_f}{\omega_{\max}^2} = \frac{275kN}{262^2} = 4.$$

Only the inertial load was considered in the analyses (force *P=0*). The calculations was carried out with the use of MATHEMATICA v. 7.0 computer code.

4. Results and discussion

The resultant resonance curve was presented in Fig. 4. Strongly nonlinear vibrations character is clearly visible. The resonance frequencies are higher that own VPH frequency 20 1/s. It must be marked that the vibrating hammers are over-resonance machines – they work above their resonance and in the presented case in this area, the amplitude is almost constant and its value is about 5 mm.

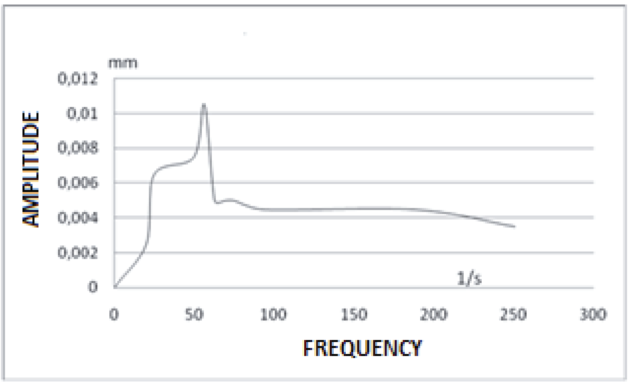

Fig. 4. Resonance curve of researched VPH

This value is almost independent from damping, which strongly influences the amplitude in the resonance and decreases with the increase of the system stiffness. The vibrations in this area are regular and periodic.

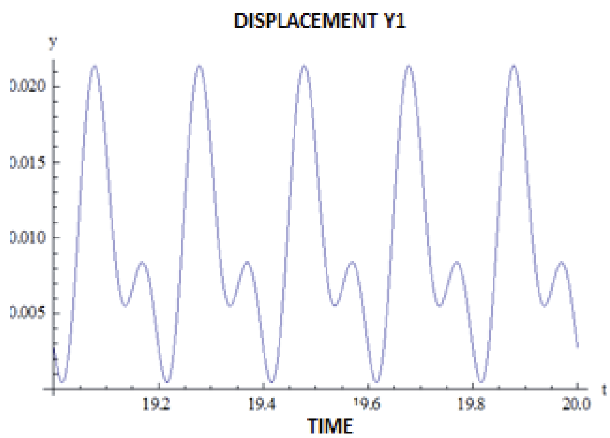

Fig. 5. Displacement curve for over resonance frequencies

It can be also concluded that in the system without damping the irregular vibrations can appear.

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