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Numerical and experimental study on soil penetration with the use of vibrating head

E. Małek*, D. Miedzińska, P. Bogusz

Department of Mechanics and Applied Computer Science, Military University of Technology, 00-908 Warsaw, Kaliskiego Street 2, Poland

Corresponding e-mail address: emalek@wat.edu.pl

ABSTRACT

Purpose: The aim of the paper is to present the numerical modeling of soil penetration with the steel cylinder and experimental research of deflection of elastomer pillows in vibrating head.

Design/methodology/approach: Simulations were performed using LS-DYNA package with two different methods to represent soil: a hybrid approach combining typical Lagrangian elements with Smoothed Particle Hydrodynamics (SPH) particles and Arbitrary Lagrangian-Eulerian (ALE) formulation. The experimental study was performed during work of the vibrating head using optical measuring methods. Two black and white cameras of high definition (1280x800) Vision Research Phantom V12 were used.

Findings: As a result of conducted numerical simulations the behavior of the soil under condition of dynamic interaction of the steel element was reflected on the base of experimental research the maximum deflection of pillows was determined.

Research limitations/implications: The modeling will be used to study the coupling of steel cylinder – soil for different soil properties and different speeds of load and its correctness was prooved. The presented results of experimental studies will be used for developing a construction of MRE regulator for vibrator resonance control.

Practical implications: Presented investigations are the part of a new vibrator construction development in which the modeling of soil and its interaction with the steel-like elements will be crucial for obtaining satisfactory results as well as a presented experiment.

Originality/value: New solutions to enhancing effectiveness for coupled mechanical systems can be achieved by using so called “smart” materials that have one or more properties that can be significantly changed in a controlled way by external stimulation.

Keywords: Magnetorheological elastomers; Smoothed Particle Hydrodynamics; Arbitrary Lagrangian-Eulerian; Ssoil modeling; Resonance; Energy efficiency

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ANALYSIS AND MODELLING

1. Introduction

Still rising requirements for coupled mechanical systems that are used in vibrating-hitting equipment for piling cause the research for new technologies enhancing their effectiveness. The construction modifications are usually insufficient. Much better results can be achieved by using so called "smart" materials, that have one or more properties that can be significantly changed in a controlled way by external stimulation.

Presented investigations are the part of a vibrator new construction development in which the modelling of soil and its interaction with the steel-like and elastomer elements will be crucial for obtaining satisfactory results. The main idea of the modification is to increase an effectiveness of the vibrator work by the regulation that will stable the vibrations in the near resonance frequency. It will be caused by the changeable stiffness of magnetorheological elastomers (MRE) which will replace, along with the regulation system, elastomer pillows in vibrator. The vibrator that will be modified is presented in Figure 1.

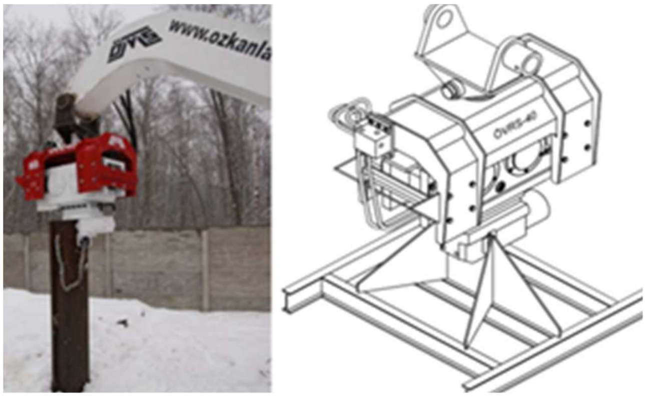

Fig.1. Vibrator OVR-S-40

Magnetorheological elastomers (MREs) are considered as smart materials. They offer variable stiffness and can be used in adaptive structures of aerospace, automotive, civil and electrical engineering applications [1, 2] for motion and vibration control.

Magnetorheological elastomers exhibit promising mechanical properties. These materials change their rheological properties depending on external magnetic field. They are similar to magnetorheological fluids, but are their solid equivalents. In magnetorheological elastomers magnetoactive particles (e.g. iron, cobalt) are embedded within elastic polymer matrix [3]. The matrix enables relatively high strains and maintains shape of the element.

The magnetorheological effect is based on dipole interactions between ferromagnetic particles [4]. Under a magnetic field, particles tend to align themselves parallel to the magnetic field lines [5]. This tendency has been used to obtain several magnetorheological elastomers with aligned chain-like microstructures. The elastomeric matrix preserves the alignment of particles after a curing process. From the authors previous research [6] it is known that aligned microstructure gives significantly greater magnetorheological effect than isotropic particle arrangement in MR composites [7, 8].

2. Numerical study

Finite Element Method (FEM) has been widely used all over the world to solve a number of various engineering and scientific problems, which are not easy to solve using typical analytical methods. Authors of the presented paper also decided to implement FE analysis for aforementioned problem of soil and steel-like elements interaction. Presented modeling provided the general idea of such phenomenon. In order to perform such task two numerical methods were implemented and compared:

- Smoothed Particle Hydrodynamics (SPH) method coupled with typical Lagrangian approach,
- Arbitrary Lagrangian-Eulerian (ALE) formulation [9].

In both analyses (SPH and ALE) the same dimensions and parameters for soil and steel cylinder were used. The cylinder was modeled with solid elements and its material was treated as non-deformable with typical steel parameters. All but vertical translational degrees of freedom were restrained. Also, for the SPH particles the symmetry was assured using boundary SPH symmetry planes. Full geometry of the penetrometer was modelled, whereas the soil segment was simulated as a quarter with symmetry conditions applied on its two walls. Also, the bottom of it was constrained. In both tests the steal cylinder penetrated the soil with a constant rate of 5000 mm/s. For the soil material (MAT_005) the literature parameters were used [9].

2.1. Modelling with FEM-SPH

Firstly, a discrete model of soil was built, using two methods:

- standard FEM,
- Smoothed Particle Hydrodynamics method (SPH).

The main difference between classical methods and SPH is the absence of a mesh. Therefore, those particles are the framework on which region the governing equations are solved [10, 11].

SPH method uses the concept of kernel and particle approximation as follows [11]:

$$\Pi^h f(x) = \int f(y) W(x-y,h) dy \quad (1)$$

where W is the kernel function, which is defined using the function θ by the relation:

$$W(\mathbf{x},h) = \frac{1}{h(\mathbf{x})^d}\theta(\mathbf{x}) \quad (2)$$

where d is a number of analyzed system dimensions and h is a spatial distance (smoothing length) over which their properties are "smoothed" by a kernel function.

The part of soil was modeled as a cuboid with dimensions of 28 0mm x 75 mm x 75 mm (height x width x thickness). A part of soil, which was subject to greatest deformation was modeled with SPH particles (80 mm x 20 mm x 20 mm) (Fig. 2). The remaining part of volume of soil was modeled using elements described by equations of Lagrange. In order to "connect" SPH particles with finite elements contact type TIED_OFFSET was used. Its interaction with soil was described by NODES_TO_SURFACE contact type. In the case of SPH particles planes of symmetry, so-called SPH_SYMMETRY_PLANES was used [11].

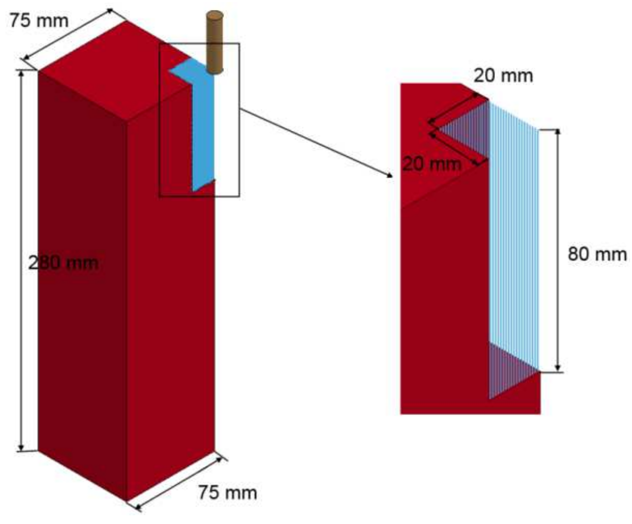

Fig. 2: Dimensions of soil model used for FE analyzes

During testing the effect of the number of particles (reduction the distance between the elements) on the results was analyzed.

Three different cases were compared (Fig. 3):
a) the number of SPH particles of 40960,
b) the number of SPH particles of 80.000,
c) the number of SPH particles of 138.240.

The number of finite elements remained constant for all cases and amounted 27400 with 31461 nodes.

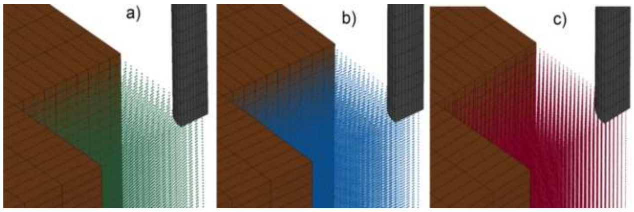

Fig. 3. Three different cases with different numbers of particles which were adopted for analyzes

2.2. MM-ALE Model

In the ALE method both the movement of the mesh, and the displacement of matter is carried out. Movement of the matter is provided with the equation [11]:

$$x = \phi(X,t) \quad (3)$$

where X is a coordinate system the matter. The function $\phi(X,t)$ is used to describe the movement of the body in the initial configuration Ω_0 to the current configuration Ω**.** This function is the same as function for mapping the displacement of the body which is described in the Lagrangian coordinate system.

The second approach is the use of the ALE method (Arbitrary Lagrangian Eulerian) which includes a description of a few different environments (Multimaterial MM). For this purpose a model of soil consisting of solid elements was built. Those elements were used for modeling both soil and air above it (Fig. 4).

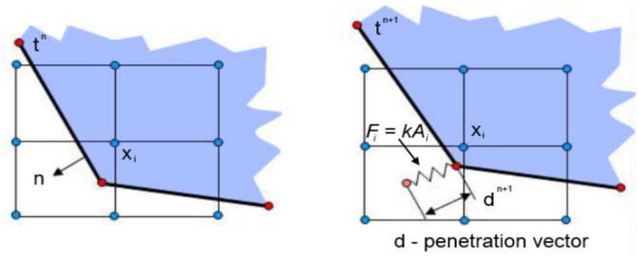

Fig. 4. Numerical coupling of environments [9]

The analyses were performed for three different mesh (Fig. 5):
a) 31428 elements
b) 251424 elements
c) 2031392 elements

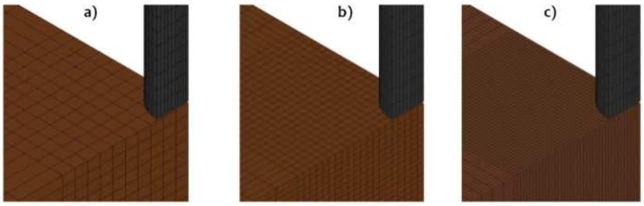

Fig. 5. Three different cases with different numbers of MM-ALE elements

2.3. Load cases

In performed analyses two types of steel cylinder load were adopted:

- a constant speed load of v = 1.5 m / s applied to all nodes of steel cylinder,
- sinusoid load of maximum (minimum) value of F = 2.5 kN, (Fig. 6).

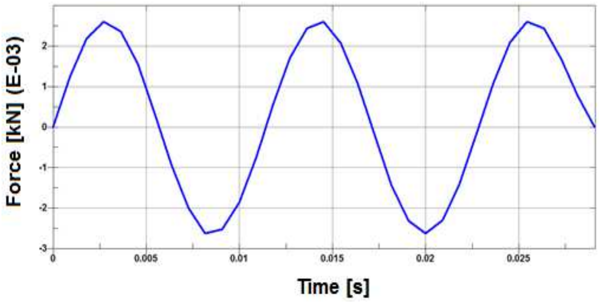

Fig. 6. Sinusoid load force adopted for computer analyzes

2.4. Material model of soil

As a constitutive model of soil was selected as MAT_005 Soil and Foam model [11]. This model is often used because of relatively small number of material constants. The material data used in the simulations was shown in Table 1.

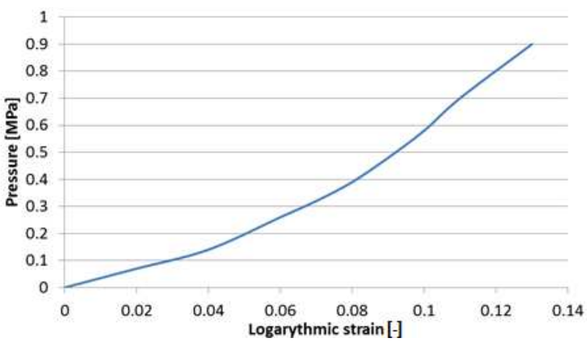

Fig. 8. Pressure curve versus strain for soil model [9]

In addition, pressure curve in a function of logarithmic deformations was defined and implemented (Fig.8).

Table 1.
Material data for soil [9]

Parametr	Description	Value
RO	Mass density	2.350e-03 [kg/m^3]
G	Shear modulus	34,474 [MPa]
K	Bulk modulus for unlo a ding	15.024 [MPa]
A0	Yield function constant	0
A1	Yield function constant	0
A2	Yield function constant	0.602
PC	Pressure cut off for tensile	0
VCR	Volumetric crushing option	0
REF	Use reference geometry to initialize pressure	0

2.5. Results of analyzes

The conducted analyzes results are shown as:

- deformation of the soil as a result of contact with steel cylinder
- velocity of a steel cylinder change (Fig.9.)
- displacement of a steel cylinder change (Fig.10.)

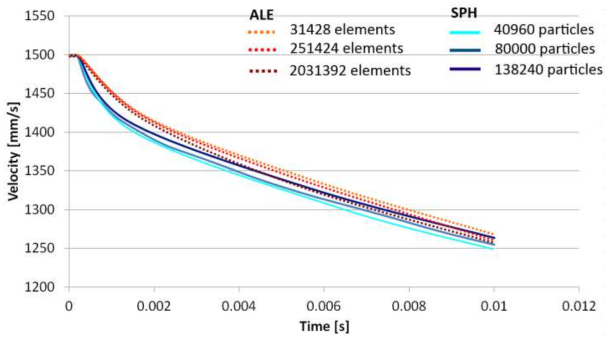

Fig. 9. Velocity change vs. time

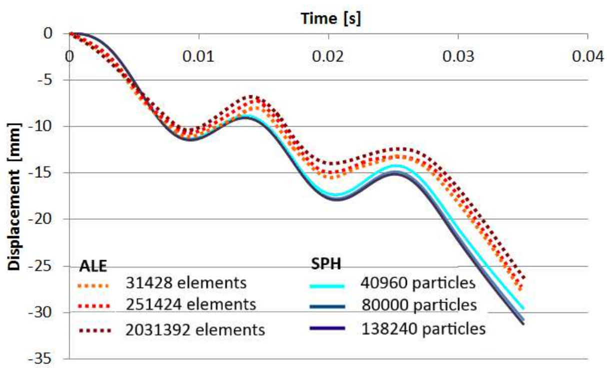

Fig. 10. Displacement change vs. time

3. Experimental study

The research on deflection of elastomer pillows in vibrating head was performed using an optical displacements and distances measurement equipment. The configuration of elastomer pillows was presented in Figure 11a). Two black-and-white cameras of high definition (1280x800) Vision Research Phantom V12 were installed in the research stage as it is shown in Figure 11b).

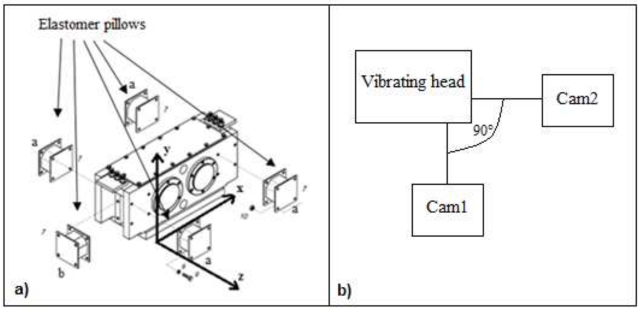

Fig. 11: a) inside construction of vibrator OVR-S-40 with elastomer pillows and directions of displacement b) cameras setting in relation to vibrating head

The first camera (marked as Cam1) was placed on a tripod, at a distance of 8.5 m from the tested vibrating head that was hanged on the excavator and fixed on the pile. The second camera (marked as Cam2) was placed approximately perpendicular to the first camera, at a distance of 8.0 m from the vibrating head.

Cameras were used for the measurement of displacement of the characteristic points at vibrating head and the relative distance between selected points. The cameras were coupled with the computer software Phantom 663ver06. Video was recorded at a rate of 1000 frames/ second. The video record was analyzed with the use of TEMA 3.3 software developed by Vision Research company.

3.1. Experiment results part 1

First camera (Cam1) results

In the measuring area of the first camera eight points were as followed: Point#1 to Point#8 and three distances: Distance#1 to Distance#3 between selected points (distance between Point#1 and Point#3; Point#2 and Point#4; Point#2 and Point#5). The camera was set perpendicular to the surface on which markers were fixed.

The moving coordinate system was located in the point 1 (Point#1). The X axis was set on the line of Point#1 and Point#2 and directed from Point#1 to Point#2. The system was changing its position with the movements of vibrating head. The selected coordinate systems was shown in Figure 12.

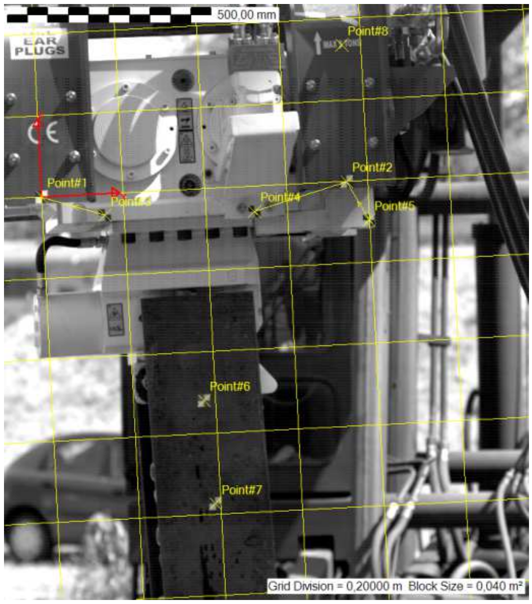

Fig. 12. Moving coordinate systems Cam1 test

In order to compensate irregular movements of the vibrating head (differences in time and distance from the camera and setting angle) image was scaled dynamically and separately for the axis X and the axis Y. Constant distance was determined between Point#1 and Point#2 (scale factor for the X axis) and Point#2 and Point#8 (scale factor for the Y axis).

On the basis of the measurement waveformed deflection of elastomer was determined vs. time in the moving coordinate system. The exemplary graphs are shown in Figure 13-16.

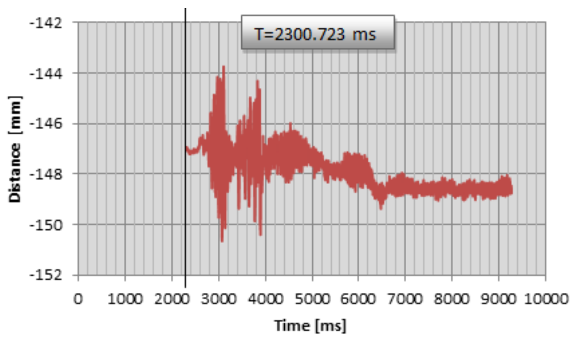

Fig. 13. Distance between Point#1 and Point#3 along X axis in moving coordinate system

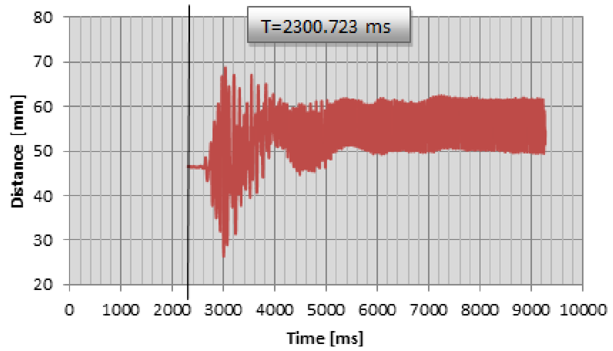

Fig. 14. Distance between Point#1 and Point#3 along Y axis in moving coordinate system

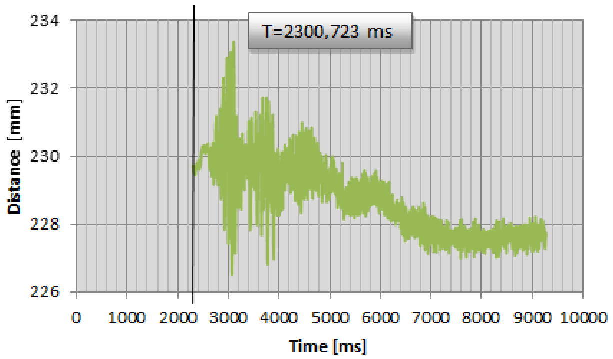

Fig. 15. Distance between Point#2 and Point#4 along X axis in moving coordinate system

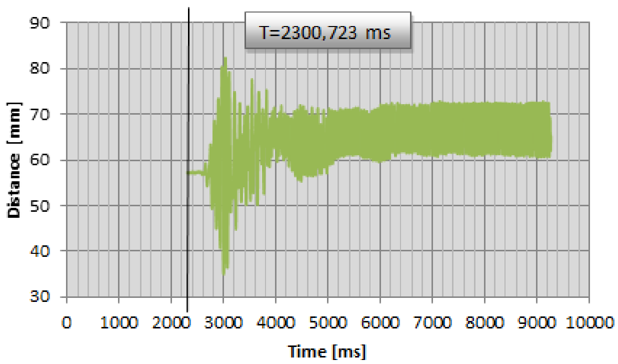

Fig. 16. Distance between Point#2 and Point#4 along Y axis in moving coordinate system

3.2. Experiment results part 2

Second camera (Cam2) results

In the measuring area of the second camera six points were followed: Point#1 to Point#6 and six distances: Distance#1 to Distance#6 between selected points (distance between Point#1 and Point#3; Point#1 and Point#4; Point#2 and Point#3; Point#2 and Point#4; Point#1 and Point#5; Point#2 and Point#5). The camera was set perpendiculary to the surface on which markers were fixed.

An example of the movie screenshot which shows location of the markers is presented in Figure 17. Distance between selected characteristic points was also shown.

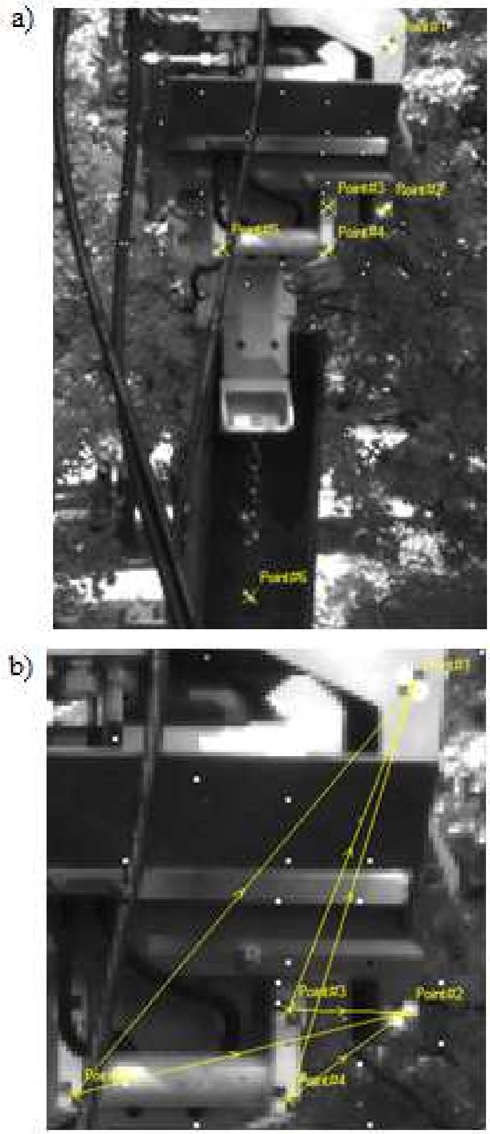

Fig. 17. Example of movie screenshot from Cam2 test, a) location of measurement points, b) distance between measured test points

In order to compensate irregular movements of the vibrating head (different in time and distance from the camera and setting angle) image was scaled dynamically and separately for the axis X and the axis Y. Constant distance were determined between Point#1 and Point#2.

On the basis of the measurement waveformed deflection of elastomer was determined vs. time in the moving coordinate system. The exemplary graphs are shown in Figure 18-22.

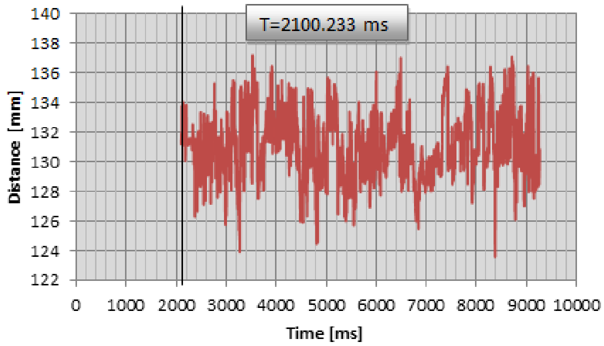

Fig. 18. Distance between Point#1 and Point#3 along X axis in moving coordinate system

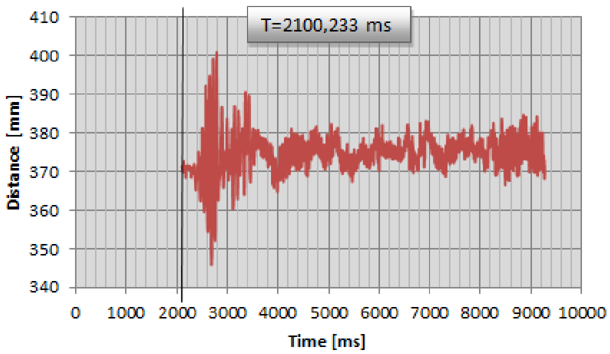

Fig. 19. Distance between Point #1 and Point#3 along Y axis in moving coordinate system

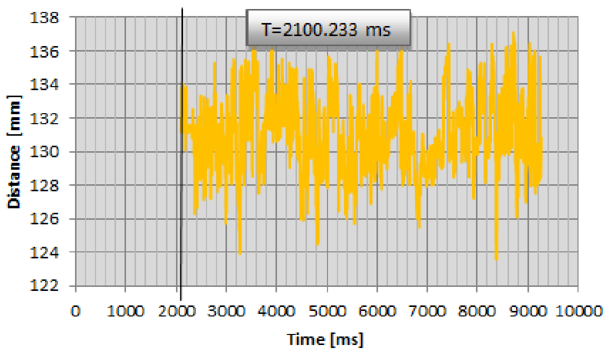

Fig. 20. Distance between Point#2 and Point#3 along X axis in moving coordinate system

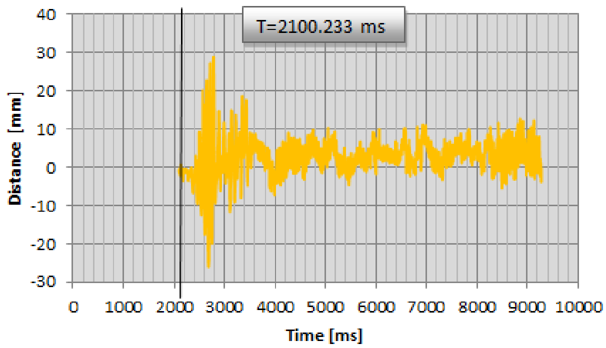

Fig. 21. Distance between Point#2 and Point#3 along Y axis in moving coordinate system

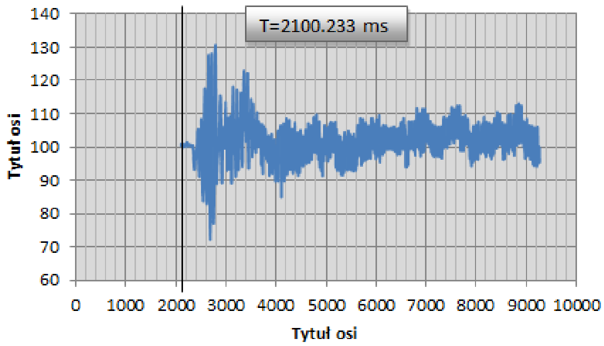

Fig. 22. Distance between Point#2 and Point#4 along Y axis in moving coordinate system

4. Conclusions

As a result of conducted numerical simulations the behavior of the soil under condition of dynamic interaction of the steel element was reflected. The following conclusions were drawn:

- The results showed that computer modeling can be very useful in this type of problems. However, attention to correct description of the applied constitutive material should be payed.
- The differences between the two methods are due to differences in the process of discretization of matter. Interactions between the particles of SPH method is performed by interpolation of physical functions, whereas in the ALE method interpolation takes place inside of the finite elements, and motion of matter is carried out without moving the mesh according to the equations of fluid mechanics. There are also differences

in the implementation method of interaction between the soil and steel cylinder.

- In both cases we are dealing with the methods that are based on the penalty function, however, in the case of the SPH method contact occurs between particles and segments of the steel cylinder. In case of the ALE method the interaction occurs between the fluid cell and the nodes of elements of the cylinder.
- Characteristics received in the analyzes showed that the used material parameters and initial-boundary conditions are correct from a physical point of view.

On the basis of experimental study of the deflection of the elastomer pillows the following conclusions were drawn:

- The maximum deflection of pillows was determined for X ,Y, Z axes. The maximum dimensional changes are presented in Tab.2.

Table2.
The maximum dimensional changes of elastomer pillows

Elastomer pillows	The maximum dimensional changes [mm]		
	X axis	Y axis	Z axis
a	+/- 4	+/- 26	+/- 27
b	+/- 4	+/- 26	+/- 27

- For pillows "a" the maximum X and Y dimensional change was assumed as maximum distance observed at Cam1 and maximum Z one was observed at Cam2.
For pillows "b" the maximum Z and Y dimensional change was assumed as maximum distance observed at Cam1 and maximum X one was observed at Cam1. The location of pillows in relation to coordinate system was presented in Figure 23.

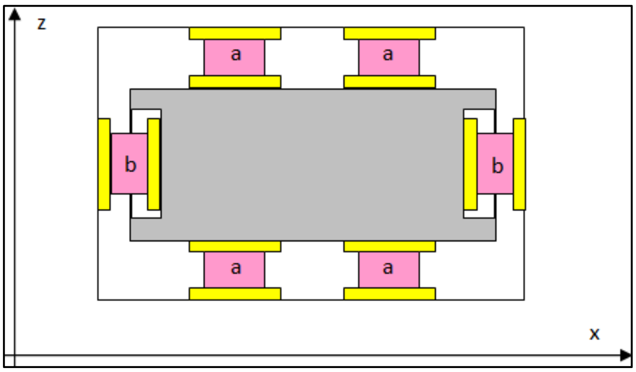

Fig. 23. View from the top of vibrating head: a, b - elastomer pillows

Finally, it can be concluded that the modeling will be used to study the coupling of steel cylinder – soil for different soil properties and different speeds of load and its correctness was prooved. The presented results of experimental studies will be used for developing a construction of MRE regulator for vibrator resonance control.

Acknowledgements

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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