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Investigation of Peak Particle Velocity Variations during Impact Pile Driving Process

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ABSTRACT: Impact pile driving is a multi-component problem which is associated to multi-directional ground vibrations. At first, vibration is transferred from the hammer to the pile and then to the common interface of pile and soil. This is then transferred to the environment and has great impact on the adjacent structures, causing disturbance to residents and also damage to the buildings. It is of high importance to have sufficient estimation of pile driving vibration level in order to maintain the comfort of residents near the site and also to prevent the structural damage to buildings. In this study, a finite element model, using ABAQUS, with the ability of simulating continuous pile driving process from the ground surface, was introduced. The model was verified by comparing the computed peak particle velocities with those measured in the field. Parameters affecting the peak particle velocity (PPV), for example elastic modulus, shear strength parameters, impact force, pile diameter, etc. were considered, and variations of PPV was investigated. Results of present study indicated that PPV at the ground surface does not occur when the pile toe is located on the ground surface; as the pile penetrates into the ground, PPV reaches a maximum value at a critical depth of penetration. Moreover, the amplitude of vibration on the ground surface reduced logarithmically with increasing distance to the pile. Also, on the ground surface and radial distances of 3 to 20 m, maximum particle velocity occurred between 1 to 5 m depths of pile penetration. The results showed PPV as being directly proportional to the hammer impact force, pile diameter, friction angle and cohesion intercept and inversely proportional to the elastic modulus of the soil.

Keywords: ABAQUS, Numerical Analysis, Peak Particle Velocity, Pile Driving.

INTRODUCTION

Anything that can change the environment, whether harmful or beneficial, is called environmental impact; where the environment may include surrounding buildings, humans and animals, soil, water, etc. In human societies, vibrations result from different sources, such as traffic, machines, hammers, explosions, earthquakes, and constructions. Pile driving impacts the environment due to the sounds and vibrations created. Nowadays, the trend in construction is towards the increasing

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demand in quality and reducing time, with minimal environmental impact. Moreover, constructions are mainly in cities adjacent to buildings, and people within the surrounding areas are affected inevitably. The adjacent structures, underground pipes, etc., may also be affected, leading to damage of equipment of effect of wellbeing of people. Sources of vibrations include explosion, excavation, destruction, dynamic compaction and pile driving. It is believed that pile driving is one of the most common sources of construction vibrations (Deckner, 2013; Karlsson, 2013).

Increasing the importance of environmental impact and construction projects in urban areas in the vicinity of residential buildings, assessment and prediction of induced vibrations due to the impact pile driving are of the important issues in the field of geotechnical engineering research. Today, the models and methods to predict vibrations caused by pile driving are inadequate. In the past decades, a number of studies have been conducted for the determination of peak particle velocity variations adjacent to the pile driving process (Wiss, 1981; Woods and Jedele, 1985; Uromeihy, 1990; Hope and Hiller, 2000; Kim and Lee, 2000; Thandavamoorthy, 2004; Massarsch and Fellenius, 2008).

Up till date, numerous numerical researches have been performed and proven satisfactory for the simulation of pile raft and pile driving process, using a software based on Finite Element Method (FEM) like ABAQUS (Sheng et al., 2005; Henke and Grabe, 2006) and based on Finite Difference Method (FDM) like FLAC (Leonards et al., 1995; Saeedi Azizkandi and Fakher, 2014). Indeed, numerical modeling is an important approach to study the phenomenon of pile driving. Sheng et al. (2005) presented an axisymmetric numerical model with a cone angle of 60°, for the toe of the pile. Their model was able to simulate pile driving installation process from the ground surface to the desired depth. Henke and Grabe (2006) proposed a three-dimensional finite element model to simulate the penetration of pile into the soil. The model was applied in the simulation of different installation methods and in investigating the phenomenon of reducing effective stresses in the vicinity of pile tip during penetration. Furthermore, they concluded that the induced vibration induced during pile driving, at the center of the pile group, affected the installation process of the other adjacent piles. Masoumi et al. (2009) presented a finite element-boundary element formulation (FE-BE) to predict vibrations due to the impact pile driving.

In most previous numerical investigations, continuous pile driving process has not been performed, and only pile has been embedded in a specific depth and then an impact applied. This approach leads to the unreal contact between pile and soil.

In the current study, numerical modeling of continuous pile driving process was conducted using ABAQUS finite element software. Special attention was paid to the variation of the peak particle velocity in radial and vertical distances from pile axis. Effects of different soil parameters and pile geometry on the amplitude of the induced vibrations were also investigated.

NUMERICAL MODELING

Using ABAQUS finite element software, an explicit scheme was adopted for the modeling of the dynamic load application by the hammer impact on the top of the pile and pile penetration into the soil.

Geometry and Boundary Conditions

Due to the axial symmetry of the geometry, loading and boundary conditions about the vertical axis of the pile, axisymmetric modeling was performed in ABAQUS software to significantly reduce the computations compared to the non-symmetric model. The model dimensions were 12 m in height and 20 m in width. To prevent the reflection of wave back into the model during pile driving process at the boundaries, infinite elements were used in the right boundary and lower side of the finite element mesh.

Figure 1 shows the geometry of the model used in present study. The length and diameter of the modeled pile were considered as 10 m and 0.5 m, respectively. In addition, to facilitate the penetration of the pile into the soil and to prevent a non-convergence numerical analysis, a tip angle of 60 degrees was used for the pile, as recommended by Sheng et al. (2005). Furthermore, a 10 mm gap was applied for soil elements, from the symmetry axis in order to prevent error due to distortion of soil elements, during pile penetration process as shown in Figure 2.

Material Properties

Mohr-Coulomb criterion is normally used for cohesive-frictional materials which have both cohesive and frictional strength components (Zhang and Salgado, 2010). This model is widely used in engineering practice, because it is relatively simple and considers a number of important aspects of actual soil behavior, using the least number of easily identifiable and familiar parameters. As shown in Eq. (1), cohesion (c) and friction angle (φ) are the major parameters of Mohr-Coulomb failure criterion. In this regard, in this study Mohr-Coulomb elastic-plastic constitutive model was used for the simulation of soil behavior.

$$\tau_f = c + \sigma' \tan\varphi \tag{1}$$

where c and φ: denote friction angle and cohesion of the soil, respectively. τ_f: is the maximum shear stress the soil can take without failure, under normal stress of σ'. Besides, dilatancy angle, ψ: is required in Mohr-Coulomb criterion to model the plastic volumetric strain increments which are actually observed in dense soils, based on the following equation proposed by Bolton (1986):

$$\varphi = \varphi_{cv} + 0.8\psi \tag{2}$$

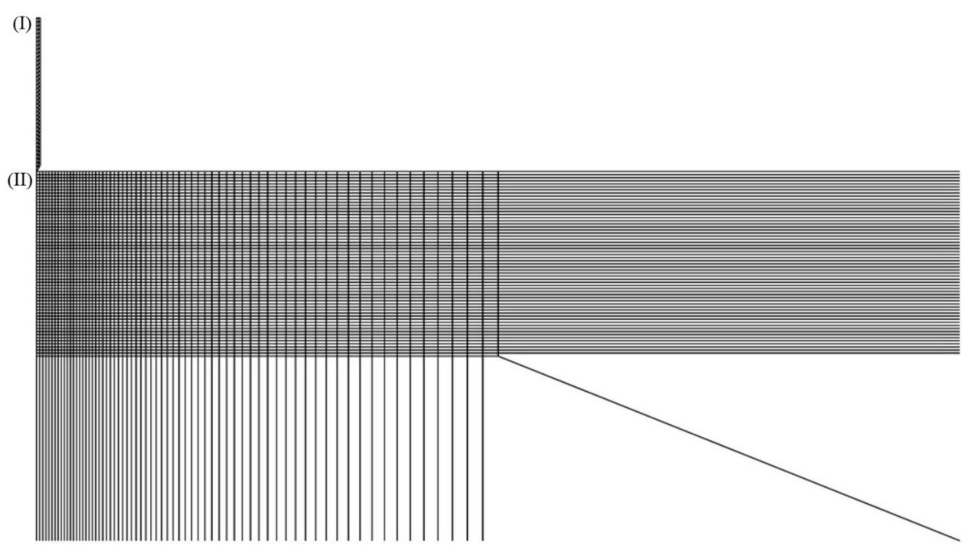


Fig. 1. Geometry of the axisymmetric model in ABAQUS: (I) pile, (II) soil

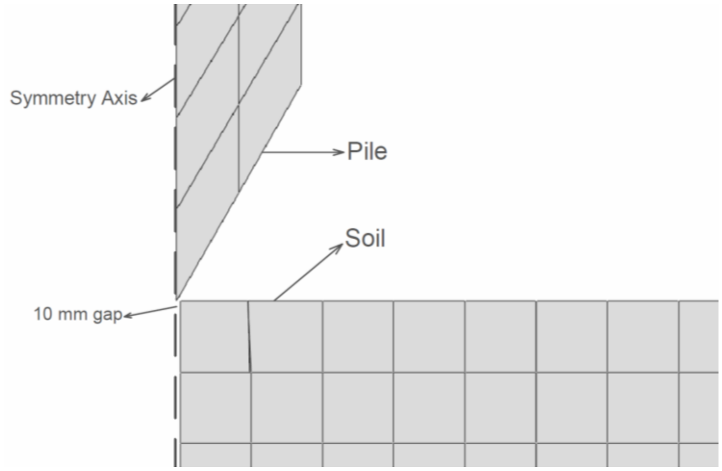


Fig. 2. A 10 mm gap between soil elements and symmetry axis

in which φ_{cv} : is the constant volume friction angle. The elastic modulus of pile is about 500 times greater than the elastic modulus of soil. As a result, the pile was modeled as a rigid material and the interface between pile and soil was considered, using penalty method, as defined in ABAQUS software, with a friction coefficient of 0.35. Moreover, damping ratio of the soil was selected as 7%.

Since pile penetration into the soil causes large deformations in the model, resulting in error due to the low quality of elements after deformation, Arbitrary Lagrangian-Eulerian (ALE) method was used to maintain the mesh and element quality during pile penetration.

Loading and Analysis

In the first step, stress analysis at rest was performed by the application of the weight of relevant elements. In the second step, successive hammer impacts at the top of the pile was applied by using the force time history shown in Figure 3 to model the pile penetration into the soil. The applied force history was similar to that used by Masoumi et al. (2009), for the verification of the proposed numerical model. It should be noted that Masoumi et al. (2009) used an analytical model which was originally proposed by Deeks and Randolph (1993), to determine the hammer impact force time history of the field experiments of Wiss (1981), as shown in Figure 3, which was also been used in present study as the hammer impact force.

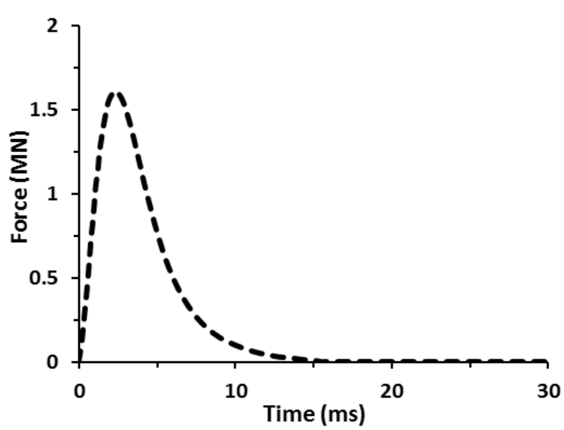


Fig. 3. Force-time history of hammer impact used in ABAQUS

In order to model pile driving process in this study, at first, pile was located on the ground and then, it was driven into the soil by the application of continuous impacts at the top. Figure 4 displays the deformed finite element mesh associated to penetration depths of 3, 6 and 9 m, respectively. As observed, pile penetrated to larger depths when greater impact energies were applied.

VERIFICATION OF THE NUMERICAL MODEL

Masoumi et al. (2009) developed a numerical model to predict the maximum impact velocity during pile driving process and verified the numerical model by the field data presented by Wiss (1981). In the present study, the selected pile and soil characteristics were similar to those in the previous studies, and their results were used to verify the numerical model. Tables 1 and 2 depict material properties for the soil and pile, respectively.

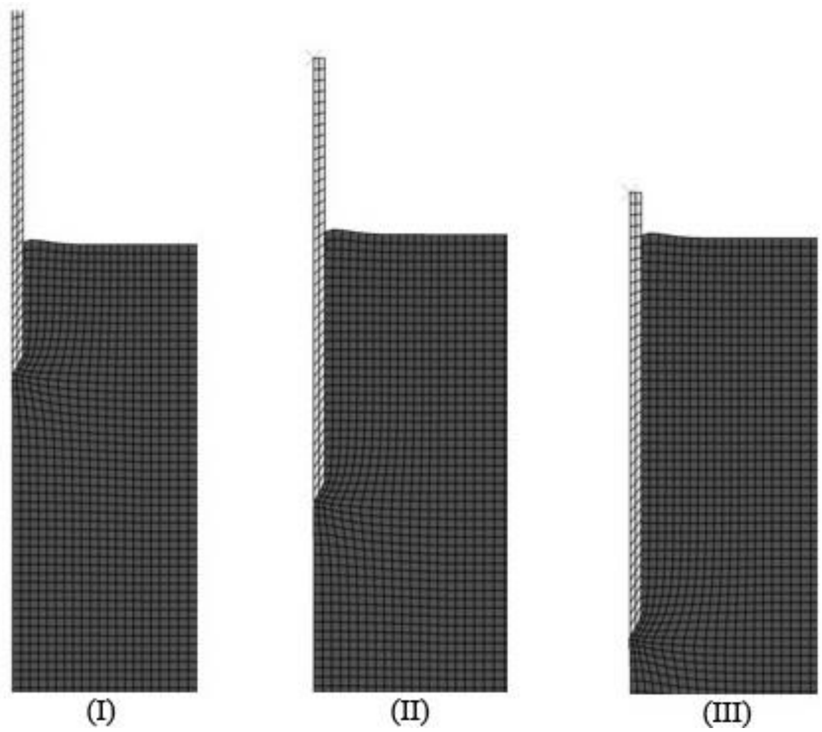


Fig. 4. Deformed mesh during pile penetration at depths of: (I) 3 m, (II) 6 m, (III) 9 m

Table 1. Soil properties used by Masoumi et al. (2009)

Soil Type	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Friction Angle (Degrees)	Cohesion (kPa)
Sandy Clay	2000	80	0.4	25	15

Table 2. Pile properties used by Masoumi et al. (2009)

Pile Type	Length (m)	Diameter (m)	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson's Ratio
Concrete pile	10	0.5	2500	40000	0.25

Figure 5 shows the variation of PPV for the developed model in the present study, on the ground surface at different radial distances from the pile axis, with measured field values of Wiss (1981) and numerical model of Masoumi et al. (2009) at three embedment depths of 2, 5 and 10 m, respectively. A comparison of the field and numerical data showed good consistency between PPV values. The predictions of this study were even closer to the field data of Wiss (1981) than that of Masoumi et al. (2009). Therefore, in despite of the fact that simulating continuous pile driving from the ground surface, instead of embedding the pile in arbitrary depth, was time consuming and required a special attention to correct the mechanism of pile penetration, it led to much better results by creating a correct contact between pile and soil.

Wiss (1981) did not measure the PPV values at depth; as a result, the developed numerical model was also compared with the numerical results of Masoumi et al. (2009) for PPV variations at depth, as shown in Figure 6. In this figure, results of both studies at depths for a radial distance of 20 m were compared when the impact was applied on pile at penetration depths of 2 and 5 m, respectively. It can be seen that the results of these models are compatible for the variations of PPV. According to Figure 6, it can be concluded that due to the appropriate and real contact between pile and soil, through simulating continuous pile driving process from the ground surface, computed PPV values in present study at both depths of 2 and 5 m predicted greater results than that of Masoumi et al. (2009).

Finally, PPV values were compared at depths for five different radial distances at full penetration depth, as plotted in Figure 7. It can be observed that PPV decreased with increase in radial distance. According to Figure 7, maximum PPV did not occur at the ground surface in all radial distances from pile axis. In other words, in near radial distances from pile axis such as 3 and 5 m, maximum PPV occurred at about 5 m depth of soil, but in greater radial distances from pile axis, such as 10, 15 and 20 m, maximum PPV occurred near the ground surface.

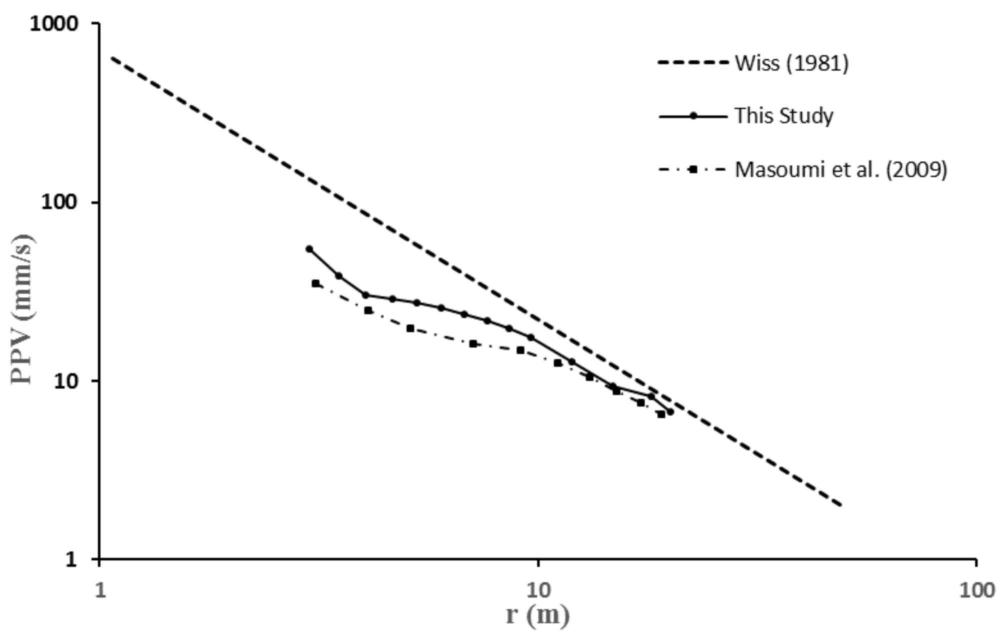
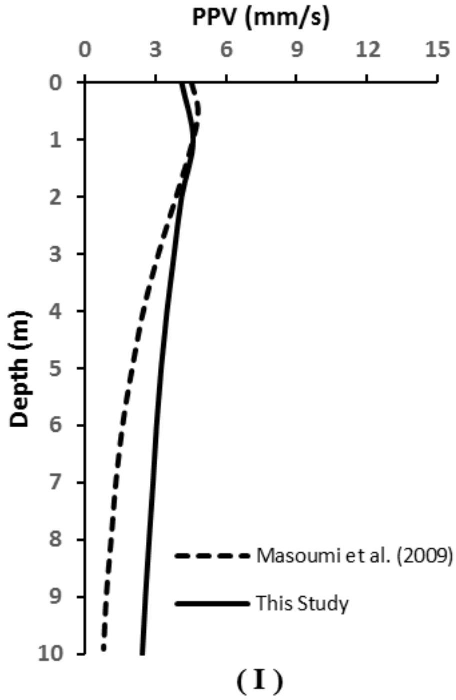


Fig. 5. Comparison of PPV values of this study with experimental results of Wiss (1981) and numerical results of Masoumi et al. (2009) considering maximum PPV at 2, 5 and 10 m embedment depths



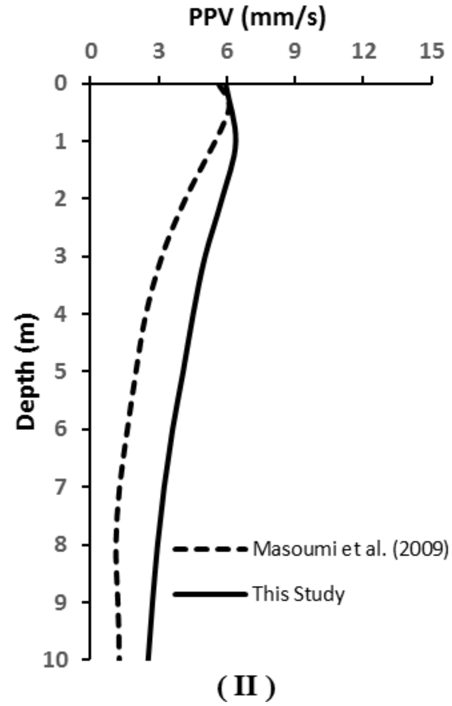


Fig. 6. Comparison of PPV values of this study with numerical results of Masoumi et al. (2009) for points located at various depths in radial distance of 20 m from the pile axis when impact on pile is applied at penetration depth of: (I) 2 m, (II) 5 m

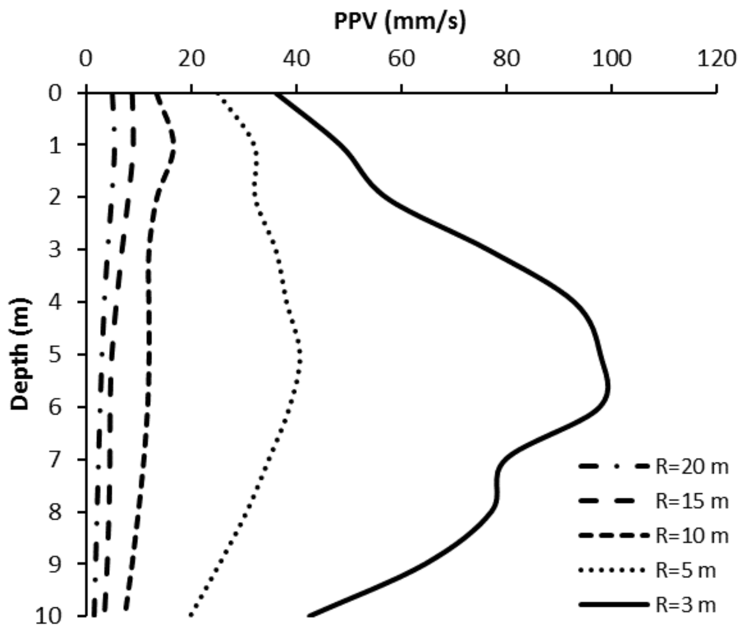


Fig. 7. PPV values computed in different depths and radial distances (R)

It should be noted that, maximum PPV on the ground surface was not induced at full penetration depth of pile. Indeed, PPV on the ground surface attained its maximum value when pile penetrated to a special depth, and this is known as critical depth of vibration. As can be seen in the Figure 8, maximum critical penetration depth for the points on the ground surface was approximately 4.2 m. Accordingly, at the ground surface, PPV occurred during pile driving process at penetration depth which was almost half the length of the pile whereas PPV did not occur during the pile penetration at depth from 5 to 10 m.

SENSITIVITY ANALYSIS

In order to investigate the influence of different factors on PPV, sensitivity analysis was performed for variation of a number of parameters such as hammer impact, pile diameter, elastic modulus, cohesion and friction angle of the soil.

Figure 3 shows a maximum impact force of 1.6 MN. Figure 9 shows the variation of PPV with radial distance from the pile axis, for the hammer impact forces of 1.6, 2.4 and 3.2 MN. It can be seen that an increase in the impact force increased the PPV values in all radial distances. So that, by increasing 50% (1.6 to 2.4 MN) and 100% (1.6 to 3.2 MN) of hammer impact force, PPV increased to about 26 and 45%, respectively.

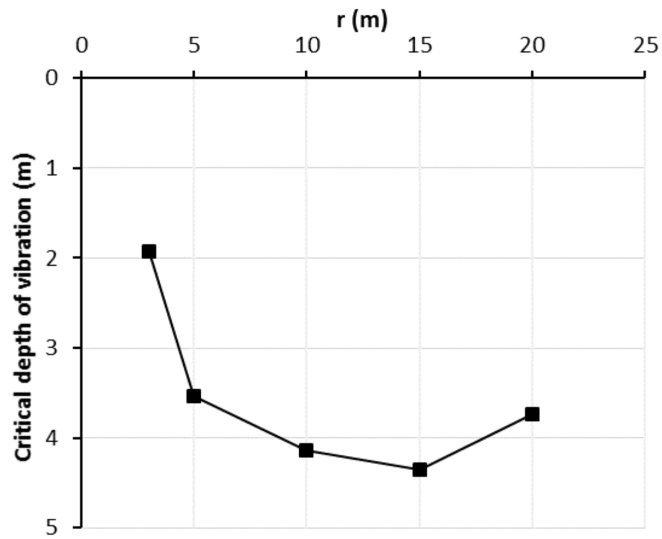


Fig. 8. Variation of the critical depth of vibration with radial distance from the pile axis

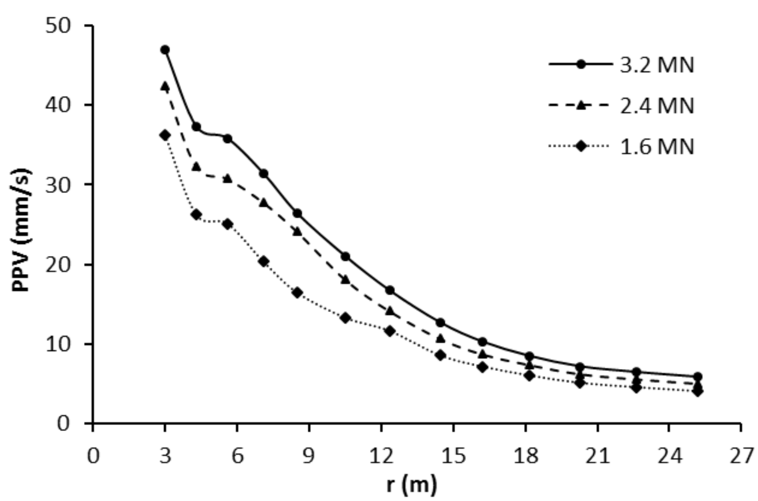


Fig. 9. Variation of PPV values on the ground surface with radial distance from pile axis for different hammer impact forces

Figure 10 displays the variation of PPV with radial distance from the pile axis for three pile diameters of 0.5, 0.7 and 0.9 m. According to the Figure, an increase in pile diameter resulted in an increase in PPV, up to the radial distance of 7 m. In larger radial distances, the effect of pile diameter on PPV can be neglected.

Figure 11 depicts velocity amplitudes for different elastic modulus of the soil. As can be seen, PPV increased by a decrease in the elastic modulus of the soil. It can be concluded that peak particle velocity was larger in softer soil compared to the stiffer soil during pile driving process. According to the Figure 11, increasing the elastic modulus of soil from 30 to 55 MPa and 30 to 80 MPa led to 20 and 38% decrease in PPV, respectively.

Figures 12a and 12b show PPV variation with cohesion and friction angle of the soil, respectively. An increase in cohesion from 15 to 75 kPa increased the PPV values from 55 to 110 mm/s. Moreover, the amplitude of velocity increased with increase in friction angle and cohesion of the soil. For a radial distance of 2.5 m, an increase in the friction angle from 15° to 35° doubled the PPV values (32 to 64mm/s). Consequently, based on Figure 12, friction angle variations affected PPV values more than the cohesion intercept for all radial distances.

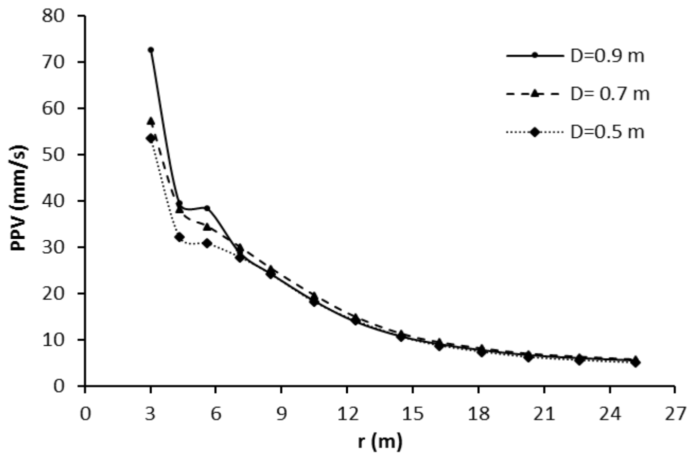


Fig. 10. Variation of PPV values on the ground surface with radial distance from pile axis for different pile diameters and the impact force of 3.2 MN

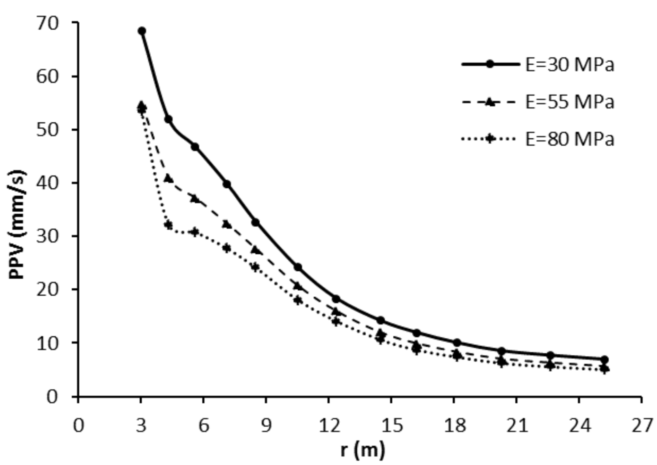
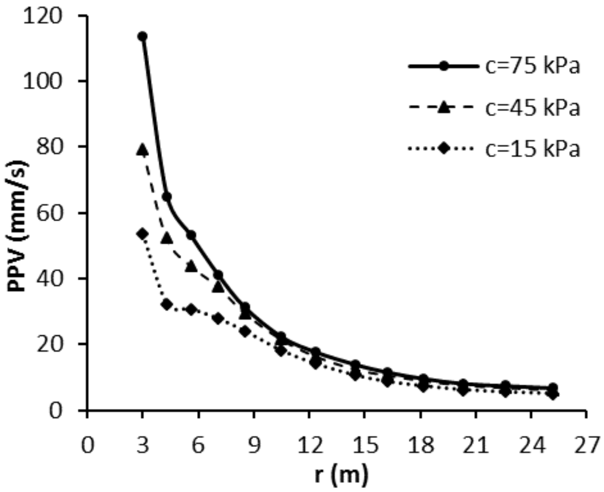
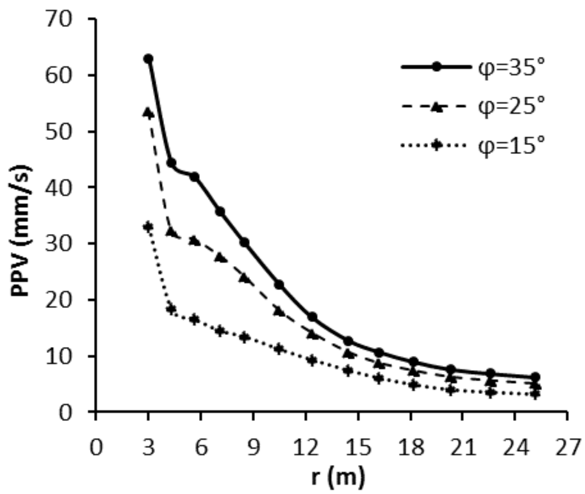


Fig. 11. Variation of PPV values on the ground surface with radial distance from pile axis for different elastic module of soil and the impact force of 3.2 MN



(a)



(b)

Fig. 12. Variation of PPV values on the ground surface with radial distance from pile axis for the impact force of 3.2 MN and various shear strength parameters of soil: a) cohesion b) friction angle

CONCLUSIONS

Despite the fact that previous studies assumed pile location in a specified depth, in the present research, continuous penetration of pile under impact force of hammer from ground surface to desired depth was successfully modeled by using ALE (Arbitrary Eulerian-Lagrangian) method and explicit scheme. The soil behavior was considered as Mohr-Coulomb and the effect of various important parameters on the peak particle velocity (PPV) in radial and vertical directions was investigated. The conclusions can briefly be summarized as follows:

- Mohr-Coulomb constitutive model implemented in numerical analysis besides ALE method and explicit scheme successfully simulated the dynamic problem of impact pile penetration into the soil and induced vibrations.
- The increase in shear strength (cohesion or friction angle) of the soil increased the peak particle velocity.
- The maximum particle velocity decreased with increase in elastic modulus of soil.
- The maximum particle velocity increased with increase in pile diameter.
- According to the numerical results, the mentioned parameters affected PPV in closer distances from the pile and their impacts can be neglected in greater distances.
- Peak particle velocity on the ground surface did not reach its maximum value at full penetration. In general, the maximum PPV occurred in a lower depth known as the critical depth of vibration.

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