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Performance evaluation of the lightweight concrete tapered piles under hammer impacts

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Abstract. Lightweight concrete (LWC) provides an attractive alternative to conventional piles by improving the durability of deep foundations. In this paper, the drivability of cylindrical and tapered piles made of lightweight and common concrete (CC) under hammer impacts was investigated by performing field tests and numerical analysis. The different concrete mixtures were considered to compare the mechanical properties of light aggregate which replaced instead of the natural aggregate. Driving tests were also conducted on different piles to determine how the pile material and geometric configurations affect driving performance. The results indicated that the tapering shape has an appropriate effect on the drivability of piles and although lower driving stresses are induced in the LWC tapered pile, their final penetration rate was more than that of CC cylindrical pile under hammer impact. Also by analyzing wave propagation in the different rods, it was concluded that the LWC piles with greater velocity than others had better performance in pile driving phenomena. Furthermore, LWC piles can be driven more easily into the ground than cylindrical concrete piles sometimes up to 50% lower hammer impacts and results in important energy saving.

Keywords: pile driving; lightweight concrete (LWC); tapered pile; field testing; signal matching; finite difference method

1. Introduction

Driven piles are commonly used as deep foundations to transmit structure loads to the ground. Precast concrete piles are constructed with controlled material and curing procedure. They are also inspected prior to and during installation and installed by impact hammering, vibrating or pushing into the ground. The design, installation and quality assurance of such piles are immensely important. Such piles must have sufficient structural strength to meet driving and design requirement.

The driving process for pre-cast concrete piles should be simulated prior to installation to ensure adequate and economic equipment selection. The dynamic testing can confirm proper hammer performance and its effect on the pile safety. The most fundamental aspects of pile analysis rely on empirical correlations based on experimental and numerical observations from real case or simulation of full scale model in three-dimensional environment. Finite element (FEM) or finite difference (FDM) methods may be normally used to get a deep understanding of the mechanical behavior of the soil–pile system during pile driving. Smith (1960) established the basis of pile driving formulation and proposed one-dimensional mathematical solution based on the time-dependent scheme that occurs as a result of a hammer impact at the pile head. In recent decades, many researchers have studied the advantages of tapered piles compared to cylindrical pile. Rybnikov (1990), Ghazavi *et al.* (1997), Wei and El-Naggar (1998), Ghazavi (2007, 2008), Ghazavi and Ahmadi (2008), Hataf and Shafaghat (2015), Ukritchon *et al.* (2016), Kumara *et al.* (2016) and Canakcila and Hamed (2017) investigated the axial static and dynamic bearing capacity of cylindrical and tapered piles. All these studies found that tapered pile had greater capacity than uniform piles of the same volume and length. This finding was proved by conducting field load tests and numerical analyses. Sakr *et al.* (2007) compared FRP reinforced concrete piles with traditional pile materials during pile driving and bearing capacity using wave equation analysis and laboratory tests and concluded that the tapered geometry had considerable effects on drivability efficiency and static resistance. Using FLAC, Ghazavi and Tavasoli (2012) performed 3-D numerical analysis of pile driving for non-uniform cross-section piles and investigated their responses. This study reveals that tapered and partially tapered piles offer better drivability performance than cylindrical piles of the same volume and length. Tokhi *et al.* (2015) established the relationship between the ultimate capacities of piles and sets in Wave Equation Analysis Programs (WEAP) using the various parameters such as pile stresses, hammer energy, capacity, damping and quakes to recalibrate the dynamic formula. Tavasoli and Ghazavi (2016) carried out experimental and numerical analyses on the drivability of hollow piles with different geometries and proved that driving hollow tapered piles was easier due to better drivability performance and lower energy consumption than concrete filled piles of the same volume and length. Sormeie and Ghazavi (2018) analyzed driven

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tapered piles' behavior into cohesive soils using the theoretical method based on cavity expansion method (CEM) in conjunction with wave equation, indicating that tapered piles were driven easier than cylindrical piles of the same length and volume. Additionally, Tavasoli and Ghazavi (2018) investigated the ground vibrations due to the drivability of non-uniform cross-section piles using field testing and numerical analysis, and concluded that the application of such piles decreases the noise pollution by reducing the operation time, applying of tapered piles considered in practice from the viewpoint of allowable ground vibrations. Tavasoli and Ghazavi (2019) analysed the drivability of stepped and tapered pile and concluded that stepped piles are more easily driven compared with cylindrical piles of the same volume and length and its' behaviour are almost similar to tapered piles and it is possible to apply them in offshore projects. Most of the above mentioned studies were carried out on piles made of common concrete and the drivability of tapered piles with lightweight concrete (LWC) is not investigated, to the best knowledge of the authors.

In structural design, there are many factors affecting the efficiency of construction technology by reducing structure weight without loss of their strength and optimizing the consumption of materials. Topcu (1997) and Al-Khaiat and Haque (1998) reported that the LWC could be defined as a type of concrete which includes an expanding agent that increases the volume of the mixture while offering additional qualities such as reducing the dead weight. The LWC maintains large voids and sufficient water cement ratio which is vital to produce adequate cohesion between cement and water. By applying the LWC to structures such as offshore drilling platforms and long-span bridges for dead load reduction, the structure members not only become stronger and lighter, but also facilitate faster construction. In addition, the LWC causes to save execution costs for structures as well as make the construction convenient (Owens and Newman 1999, Choi *et al.* 2006, Maraveas, 2018). Kilic *et al.* (2003) and Cusson and Hoogeveen (2008) reported that the lightweight aggregate could be a natural or artificial one. The main characteristic of these materials is high porosity that results in a low specific gravity. These aggregates were usually saturated prior to use in concrete to ensure adequate workability, since it was recognized that dry porous aggregates could absorb some of the mixed water in fresh concrete. The LWC is categorized into two types of partially compacted and structural according to its application. The shape and the texture of the aggregate particles and the coarse nature of the fine aggregate tend to produce harsh concrete mixes. However, the use of LWC in underground structures such as driven piles seems to be both attractive and controversial choice.

In the present paper, the drivability of cylindrical and tapered piles made by the different lightweight and common concrete (CC) have been investigated using field testing under multi hammer blows. The different types of LWC and CC piles with different properties were considered and the wave propagation in elastic LWC rods was analyzed. The signal matching and pile driving system is simulated and the measured results from experimental tests were presented, compared and discussed.

2. Field testing program

In this study, the field testing program aims to investigate the effect of concrete material properties and in the drivability of tapered and cylindrical piles in the field tests which driven into soil with multi hammer impacts.

2.1 Tapered and cylindrical concrete piles

The cylindrical and tapered piles used in this study were made of two types of reinforced concrete including lightweight concrete (LWC) and common concrete (CC). All piles had 250 cm length with conic toe. Pile C was cylindrical with 75mm radius and pile T was fully tapered with 1.1° tapering angle, 100 mm top and 50 mm toe radius. Both D_f/D_p and L_p/D_p of piles are greater than 10, where D_f, D_p and L_p are respectively the depth of foundation and the diameter and length of pile, resulting to act such as deep foundations, As mentioned by Tavasoli and Ghazavi (2018). Therefore, the obtained results can be extended to real piles and used in practice. It is important to notice that these filed tests are only real available tests in the literature which performed on cylindrical and tapered LWC piles. The concrete mixtures were considered to compare the mechanical properties of light aggregate and about 10% of the natural aggregate volume was replaced with light aggregate. All concrete mixtures were prepared with 500 kg/m^3 of cementation material, e.g., 450 kg of Portland cement was mixed with silica fume equal to 10% of the cement weight (Kilic *et al.* 2003). The rate of super plasticizer admixture was fixed at one percent of cement weight to achieve the desired performance. The standard 15 cm cube specimens were constructed and tested for compressive strength based on codes. The amounts and proportions of lightweight and common concrete mixtures were shown in Table 1. The CC had a compressive strength of 45.2 MPa for cubic samples and 40.4 MPa for cylindrical samples, and LWC had more compressive strength than CC with 51.2 MPa for cubic samples and 45.7 MPa for cylindrical samples. Also, the specific weight of LWC and CC were respectively measured 1820 and 2310 kg/m^3. This, the weight loss for the LWC was about 20~25% compared with that of the CC.

2.2 Soil properties

The non-cohesive soil bed was located in Tehran with poor-graded sand based on Unified Classification System and its grain size distribution is shown in Fig. 1. The peak frictional angle, f_p, and residual frictional angle, f_r, determined from direct shear tests were 29° and 24°, respectively. The mechanical properties of soil are also given in Table 2.

2.3 Strain and velocity monitoring method by pile driving analyzer

The Pile Driving Analyzer (PDA) is a tool to control the pile driving which applied for dynamic pile monitoring

Table 1 LWC and CC concrete mixtures and properties in this study

Type		CC	LWC
Cement (kg)		500	450
Microsilica (kg)		-	50
Fine agg. (kg)		900	700
Coarse agg. (kg)		850	620
Water (kg)		150	150
r_{wet} (kg/m^3)		2400	2000
Cubic Compressive Strength (MPa)	10 days	30.9	37.1
	42 days	45.2	51.2
r_{dry} (kg/m^3)		2310	1820
E_s Measured (Gpa)		24.1	19.8

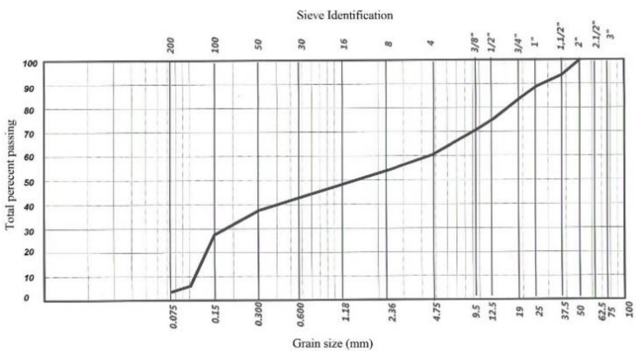


Fig. 1 Soil classification chart of tests site

Table 2 Soil parameters in this study

Soil	f (deg)	w (%)	D_r (%)	n	E (MPa)	g (kN/m^3)
Bed	16.2	22	0.3	62	0	24

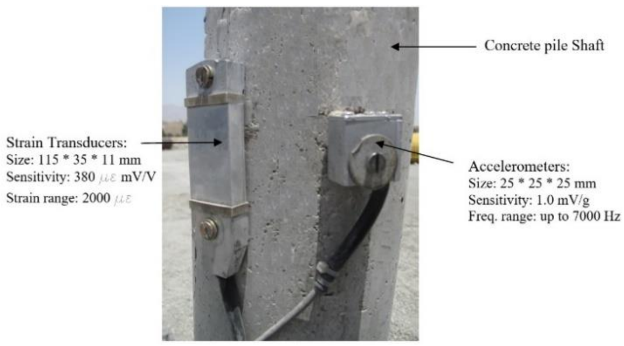


Fig. 2 Strain transducers and accelerometers sensors

(DPM) and dynamic load testing (DLT). The DPM is conducted during the impact driving of piles to contribute to a safe and economical installation. The most important results of this test are hammer performance, dynamic pile velocity, penetration and stresses during driving. The DLT was conducted independent of the pile installation process to assess pile bearing capacity. The PDA is based on theory of stress wave propagation on piles, and involve accelerometers and strain transducers attached the pile shaft about two to three pile diameters below pile top (Ghazavi and Tavasoli 2012, Tavasoli and Ghazavi 2012, 2018). For each impact of drop weight or hammer blow to the pile top, the sensors acquire acceleration and strain signals which recorded continuously and transferred to a PC. The PDA conditions, digitizes, stores the signals and computes the forces and velocities at the pile head and performs automatic calculations. The dynamic load testing instruments consist of two strain gauge circuits and two velocitimeters attached along the pile shaft externally at least two and preferably three diameters below the pile top to avoid end effects and local contact stresses, as shown in Fig. 2. The time histories of the head forces and velocity were monitored continuously during driving tests.

3. Test results and observation

Pile driving tests were conducted on four tapered and cylindrical piles made by LWC and CC materials. All piles were installed to an embedded length of 0.5 m to 2 m using a single acting hammer with a 300 kg mass falling from a height of 1m onto a 20-mm thick plywood cushion which suggested by Jonker and Foeken (2000) to increase the efficiency of double acting hammers. The pile driver was composed of a mounting frame, hammer and electric motor which lifted the ram to the selected falling height, and then the hammerhead fell to induce an impact on the hammer components. The strain gauges and accelerometers were bolted along the pile shaft externally at 32.4 cm from the pile head in two opposite directions to record the settlement and velocity of piles. The pile geometry, field testing conditions and equipment views have been illustrated in Fig. 3. If the hammer is not working well, the transferred energy will be relatively low and it will take longer to drive the pile so productivity suffers. If the hammer is not performing well and a blow count or set per blow is used as the pile acceptance criteria, then the pile could be accepted prematurely at a lesser pile penetration and the actual pile capacity could be dangerously too low and foundation failure could result. To avoid the possible dispersion of soil condition in the site and the resulting effect on the test results, several parallel tests were also conducted on piles with different geometries and the obtained results were compared.

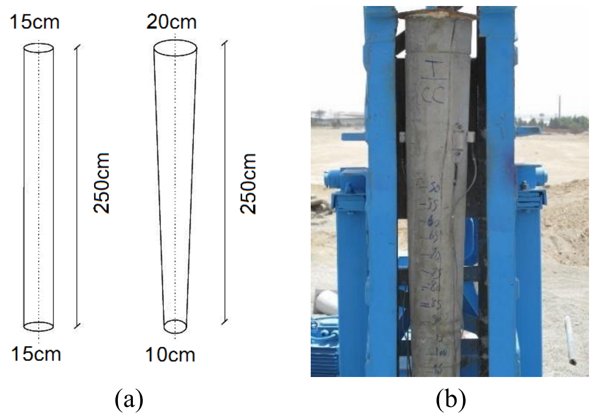


Fig. 3 Oblique view of (a) pile dimensions (b) pile driving equipment

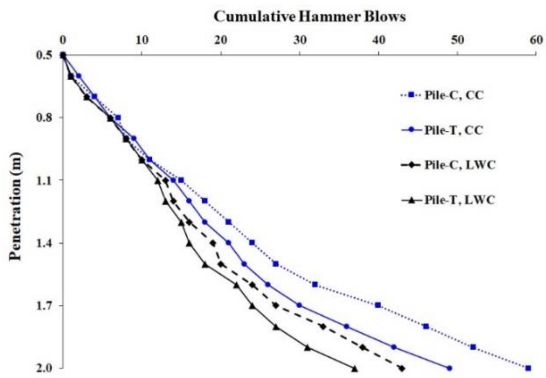


Fig. 4 Cumulative hammer blows of different piles geometry with LWC and CC

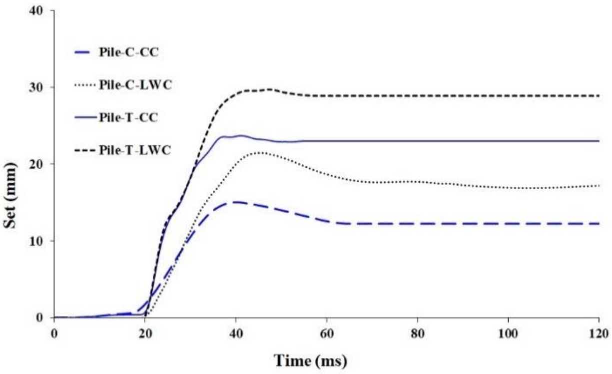


Fig. 5 Measured settlement of piles with different concrete properties

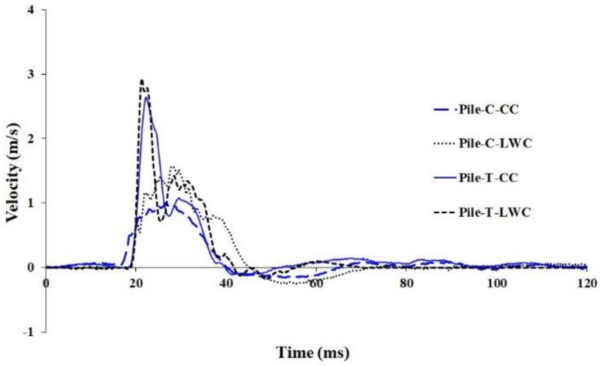


Fig. 6 Measured velocity of piles with different concrete properties

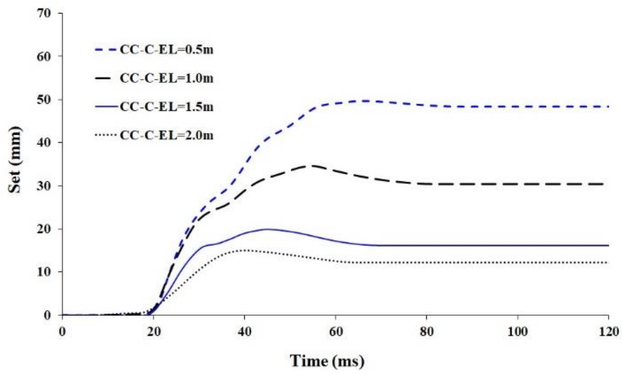


Fig. 7 Comparison of pile C-CC settlements for various pile embedded length

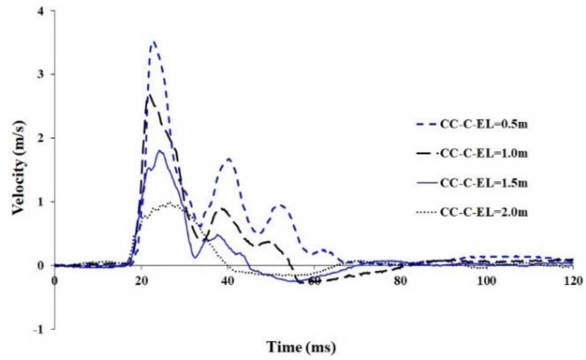


Fig. 8 Comparison of pile C-CC velocity for various pile embedded length

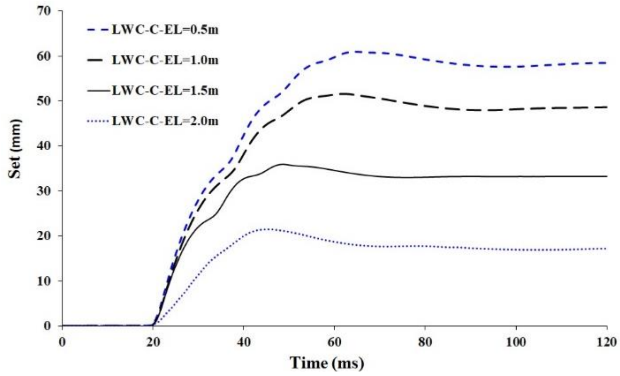


Fig. 9 Comparison of pile C-LWC settlements for various pile embedded length

Fig. 4 shows the driving records of cylindrical and tapered piles in terms of measured cumulative hammer blow counts versus the penetration depth. It was observed that all piles showed approximately similar driving behavior up to the penetration depth of 1 m. There were maximum 37 and 49 blow numbers required to drive T-LWC and T-CC piles into predicted embedded depth. Piles C-CC and C-LWC required 50 and 43 hammer impacts respectively to penetrate into the ground. At higher penetration depths, the cylindrical pile required more number of blows than tapered piles to achieve the same final penetration and LWC piles required less number of blows than CC piles.

The measured settlements and velocity of piles versus time for final hammer blows are shown in Figs. 5 and 6. The residual sets of cylindrical and tapered pile made by common concrete were recorded to be 12.26 and 23.01 mm, respectively. For LWC pile, the settlement in final set of pile C was measured 17.05 mm and 28.98 mm in pile T. The results showed that the settlement and velocity of tapered piles were greater than those of uniform cross-sectional piles. In addition, LWC piles had better performance than CC piles in terms of increasing velocity and residual set per blow. The cause of increasing penetration rate of the tapered piles relative to the cylindrical piles was the reduction of the soil resistance concentration at the pile tip and its uniform distribution along the pile shaft. Therefore, by decreasing hammer blow counts and increasing pile penetration, it can be concluded

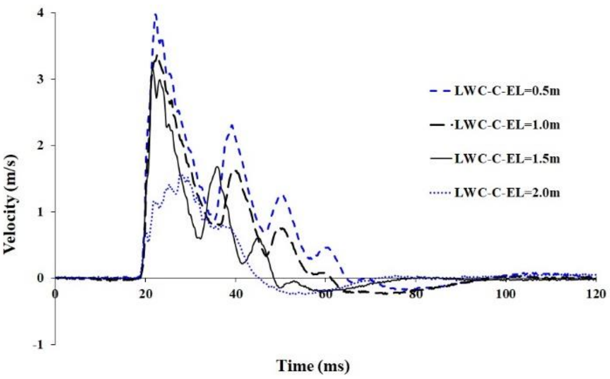


Fig. 10 Comparison of pile C-LWC velocity for various pile embedded length

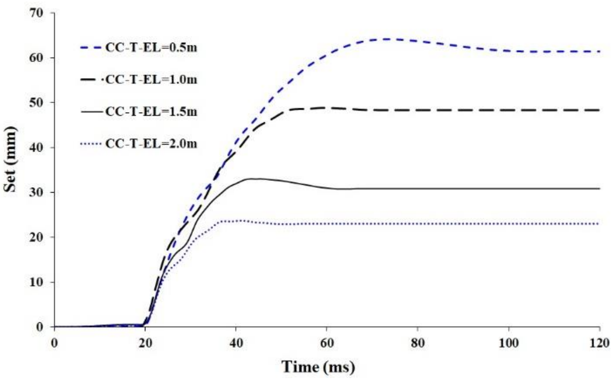


Fig. 11 Comparison of pile T-CC settlements for various pile embedded length

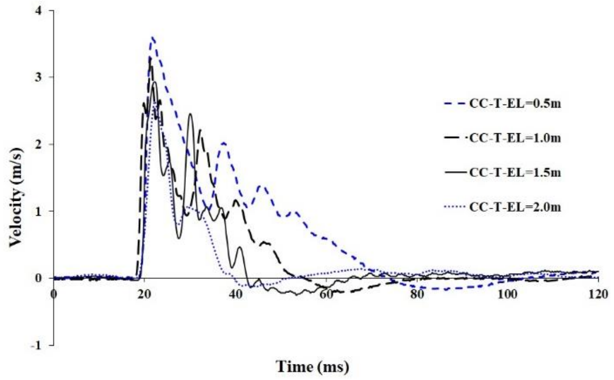


Fig. 12 Comparison of pile T-CC velocity for various pile embedded length

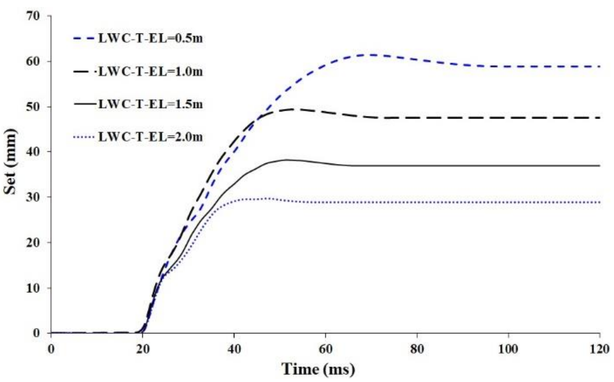


Fig. 13 Comparison of pile T-LWC settlements for various pile embedded length

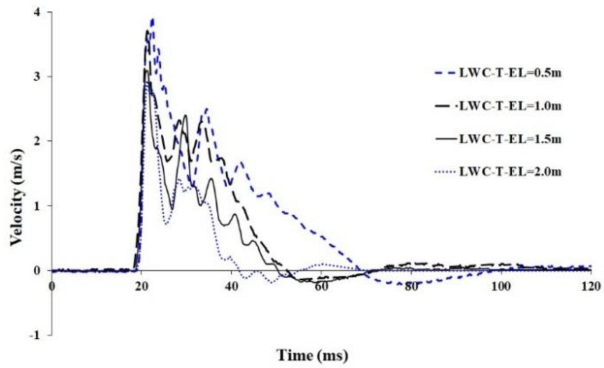


Fig. 14 Comparison of pile T-LWC pile velocity for various pile embedded length

that LWC piles have a better performance and effect in pile settlements and energy and economical saving.

As mentioned above, all piles were penetrated from 0.5 m to 2 m in the soil and pile head velocity and set were monitored per blow. Thus, the effect of embedded length on drivability of different piles was also studied. The results of piles' settlement and velocity in embedded length of 0.5 m, 1 m, 1.5 m and 2 m were shown in Figs. 7 to 14. It was observed that with increasing embedded length of pile in the soil, the settlement of pile decreased due to increasing soil-pile interaction.

As mentioned above, the effects of pile concrete materials and geometry on driving were investigated by performing field testing and comparing between measured data. It is obvious that the behaviour of piles changed by varying its material and geometry at different penetration depths. The results indicate that tapered piles have a better drivability performance than cylindrical pile of the same volume and length, as seen in Fig. 15, in which H_{em}/L_{em} is the ratio of the penetration depth to embedded length of piles. The cumulative number of hammer impacts required to drive different piles into the ground to a certain depth is first calculated for all piles. The number of blow counts for each pile driven to a certain depth is divided by the number of blows required to drive the C-CC pile to the same depth. It is noted that for calculating this ratio, common concrete for the pile material is used for the cylindrical pile. This ratio states that tapered piles made of common and lightweight concrete offer better drivability performance with an energy reduction ranging 20-50%, compared with the cylindrical pile of the same volume and length. It is noted that in cylindrical piles, the pile toe cross section is constant and thus the tip resistance is approximately constant while the pile is penetrating into the ground. While in tapered piles, the pile shaft gradually expands the cavity and thus a gradual soil resistance increase exists with the pile penetration into the ground (Sormeie and Ghazavi, 2018).

Fig. 16 indicates the variations of penetration rate to the number of blow count of tapered and cylindrical piles with LWC and CC. As shown, the efficiency of the drivability of the tapered piles is greater than that of the cylindrical pile with increasing penetration rates for lower blows. The lightweight concrete pre-cast piles also have a better performance than common concrete piles. Thus, the final

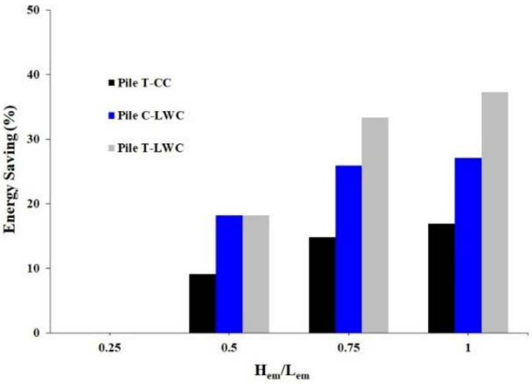


Fig. 15 Comparison of energy saving by using different piles property and geometry

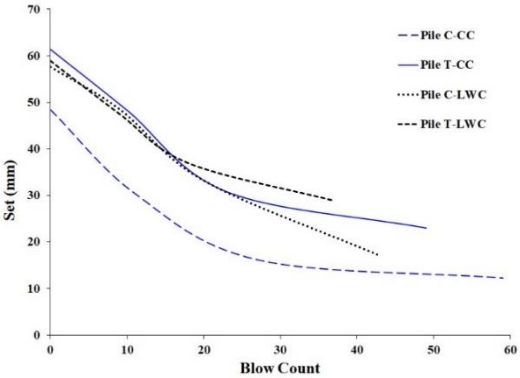


Fig. 16 Variation of penetration rate to the blow numbers of T and C piles with LWC and CC

(a) (b)

Fig. 17 Comparison of the pile head at the end of driving: (a) Tapered pile and (b) Cylindrical pile

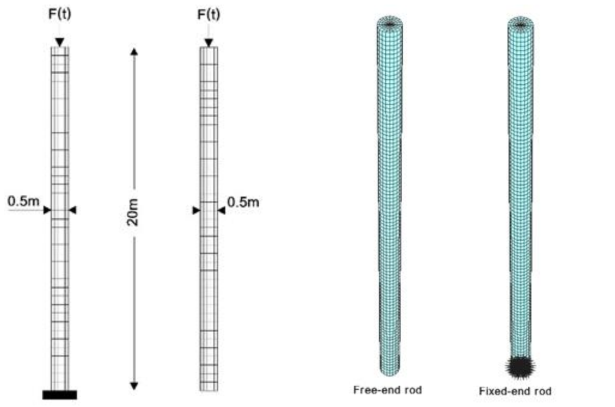
penetration ratio to the number of blow count is equal to 78% for pile T-LWC and 40% for pile C-LWC which is greater than that of the calculated ratio for prefabricated CC piles.

One of the important concerning major with pile driving are noise, air pollution and pile safety due to hammer impacts. As shown above, the geometry and LWC materials for piles result in decreasing the number of hammer blows and thus increasing the driving efficiency. Therefore, the use of these piles can also reduce the environmental pollution and noise caused by pile driving. The pile safety is also very important during pile driving. Fig. 17 shows that during driving, the head of one cylindrical pile was broken due to driving stress while no breakage occurred to tapered pile. This is due to larger cross-section of the tapered piles at the head which is larger than that of cylindrical pile. Therefore, compared with cylindrical piles, tapered piles not only experience lower driving stresses but also their final penetration is greater under any impact. These characteristics are accelerated in LWC tapered piles. It can be said that the tapered pile has greater head cross-section than a cylindrical pile. Thus, driving stress decreases in tapered piles compared with cylindrical piles. Another contributing factor is the compressive strength of concrete. The LWC has greater strength than CC, as indicated in Table 1. The authors observed no damage during the drivability of LWC tapered piles. Although lower driving stresses are induced in the LWC tapered pile, their final penetration rate is more than that of CC cylindrical pile under hammer impact. This is advantageous for using tapered piles in practice.

4. LWC piles driving investigation by finite difference method

In order to find the reasons for the better performance of lightweight pre-casted piles compared to CC, wave propagation pattern is studied for piles. To this aim, some analyses of elastic rods with different concrete properties and boundary conditions are performed considering wave propagation and signal matching in rods. The procedure used in these analyses is as same as the PDA test output in which the force (F) and the wave velocity (v) variations with time are plotted and velocity is multiplied by the rod impedance (Z_p=E_p.A_p/v) to be equivalent to force (Z_p.v), where E_p and A_p are the elastic modulus and cross-section area of pile (Masouleh and Fakharian, 2008; Ghazavi and Tavasoli, 2012). Fixed and free-ended elastic rods have 20 m length and 0.25 m radius and rod gravity was neglected and no soil or other supports were considered around the rod shaft in the analyses, as observed in Fig. 18. The elastic modulus, Poison's ratio and specific weight of CC and LWC are shown in Table 1. The hammer blow on the rod head was simulated by a half-sine stress wave with amplitude of 5 MPa and frequency of 320 Hz (Masouleh and Fakharian 2008). The force and velocity records were monitored at 5 m below the rod head to represent the dynamic responses. The calculated signal matching of rod with different LWC materials in comparison with common concrete have been illustrated in Figs. 19 to 22.

The downward settlement of a particle on the rod section shows a positive velocity and the upward settlement shows a negative velocity. Figs. 21 and 22 show that after a time required for stress wave to travel between the record point at 5 m below the rod head to rod tip and return to the same point equivalent to 2L/C, F wave is suddenly shifted up and Z_p.v wave is shifted down and their amplitudes are equal to the generated wave amplitude. This observation is exactly in accordance with one dimensional wave propagation theory in rods without damping. The immediate F and Z_p.v waves shifted down after tip reflections are the reflections from the rod free head boundary condition, as explained by Fiezi Masouleh and Fakharian (2008). In fact,



(a) (b)

Fig. 18 Three-dimensional LWC and CC rods with different boundary conditions

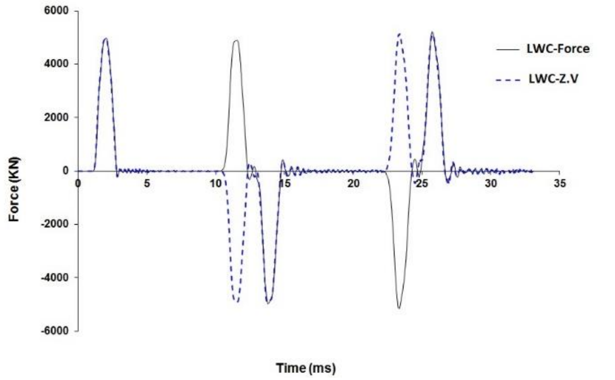


Fig. 19 Signal matching of LWC rod in fix-ended condition

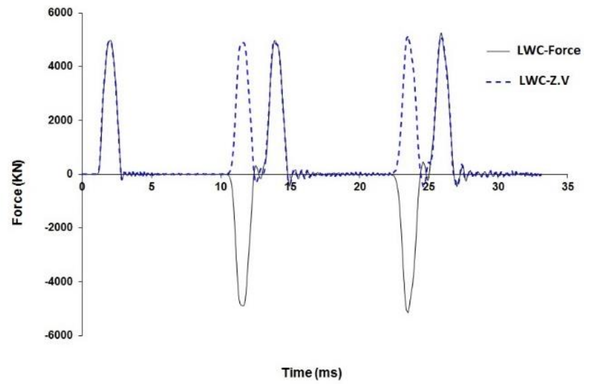


Fig. 20 Signal matching of LWC rod in free-end condition

the downward initial compressive wave is reflected as compression type at rod fixed-end and reflected tension type at the rod free-top boundary conditions. These observations were exactly in accordance with the one-dimensional wave propagation theory in rods without damping. Wave velocity in the concrete rod depends on elastic modules and specific weights and calculated 3230 m/s for CC rod and LWC rod had the velocity of 3298 m/s. Thus, the LWC rod has greater velocities than the CC rod. This is interesting and has an important role in signal matching and therefore, it could be concluded that the LWC with greater velocity than others must have better performance in pile driving phenomena.

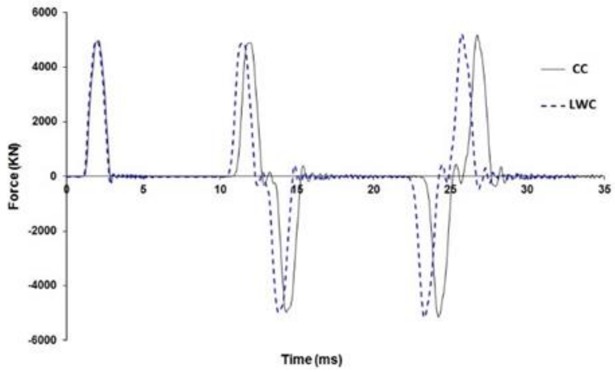


Fig. 21 Dynamic responses of LWC and CC rods in free-ended condition

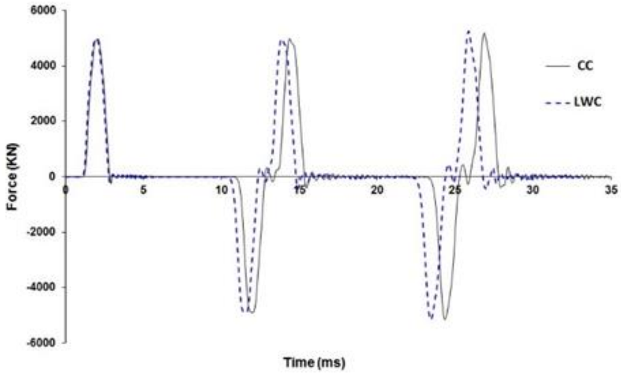


Fig. 22 Dynamic responses of LWC and CC rods in fix-ended condition

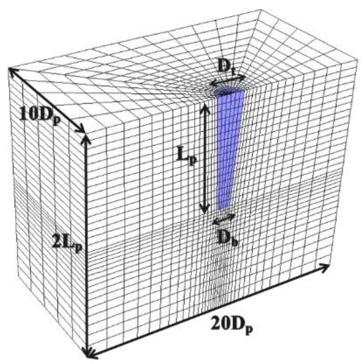
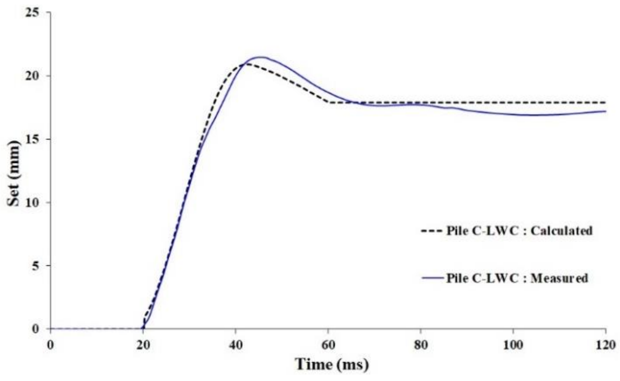


Fig. 23 Three-dimensional LWC pile-soil system in numerical analysis

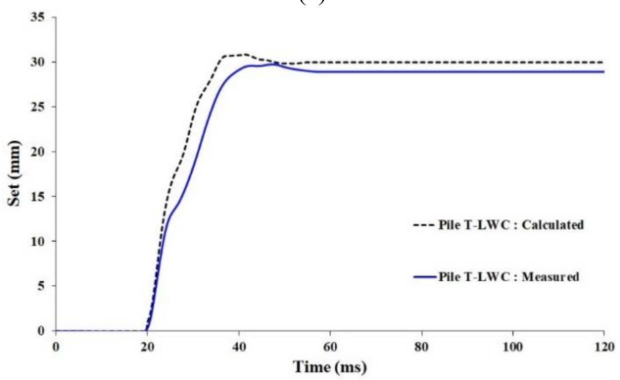
Table 3 Properties for Interface elements used in numerical analysis

Interface strength parameters		Interface deformation parameters	
Friction angle (deg)	Cohesion (kPa)	Shear stiffness, K_s (MN/m^2/m)	Normal stiffness, K_n (MN/m^2/m)
16	0.1	148	1.48

In this section, the drivability of pre-cast cylindrical and tapered piles with different concrete material properties are investigated by finite difference method based on FLAC3D software. Based on explained field tests, all model

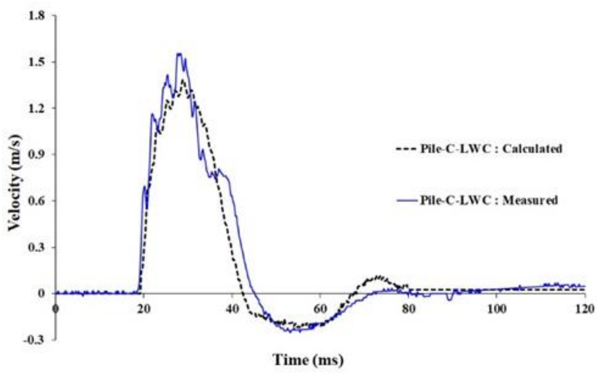


(a)

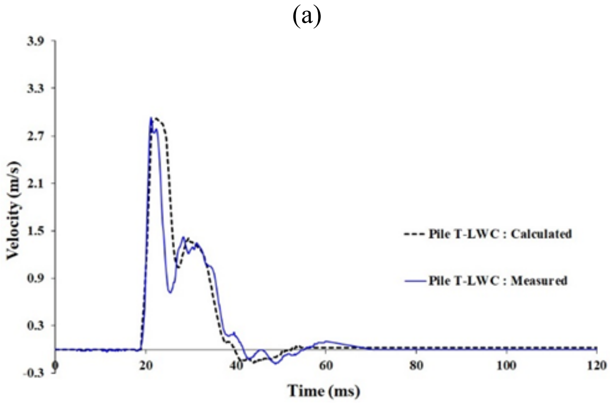


(b)

Fig. 24 Settlement comparison between measured and calculated results due to driving of (a) Pile C-LWC and (b) Pile T-LWC



(a)



(b)

Fig. 25 Velocity comparison between measured and calculated results due to driving of (a) Pile C-LWC and (b) Pile T-LWC

Table 4 The different LWC mixtures and properties in present study

Type		CC	L1	L2	L3	S1	S2	S3
Cement (kg)		-	450	450	450	450	450	450
Microsilica (kg)		-	50	50	50	50	50	50
Fine agg. (kg)		-	315	260	205	595	501	407
Coarse agg. (kg)		-	730	860	990	728	858	977
Water (kg)		-	150	150	150	150	150	150
γ_{wet} (kg/m^3)		-	1715	1790	1865	1998	2034	2070
γ_{dry} (kg/m^3)		2400	1585	1660	1735	1868	1904	1940
Cubic Compres. Strength (MPa)	10 days	-	33.20	36.29	40.85	45.35	50.46	54.63
	42 days	-	30.54	33.75	38.40	39.00	43.90	48.62
E_s (Gpa)		24.86	14.90	15.67	18.57	16.88	21.27	19.30
ν		0.20	0.19	0.18	0.19	0.20	0.22	0.22

Table 5 Soils properties in present study

Soil	γ (kg/m^3)	ν	C (MPa)	φ (°)	E (MPa)
Clay	1600	0.35	2z	0	10
Sand	1900	0.30	0.1z	30	75

geometry, boundary and initial conditions, mechanical properties of soil and piles are considered according to the field test conditions reported by Ghazavi and Tavasoli (2012) and Tavasoli and Ghazavi (2016, 2018) on tapered pile driving. Fig. 23 shows side and bottom boundaries in numerical simulation. The soil was assumed to be elasto-plastic material which obeyed the Mohr-Coulomb failure criterion and the pile had elastic behavior. Fine meshes were allocated to the model and grid definition was refined under the tip of the pile and along the pile shaft. A force function recorded with PDA was applied to idealize and simulated the hammer impact on the pile head. Roller type supports were used to allow movement in the vertical direction and resist grid settlements. To prevent wave reflection into the model at the different location in boundary condition, quiet boundaries were also considered. The pile-soil interaction are simulated using interface elements along the pile shaft and at the pile toe during pile driving procedure to control the slip at the soil-pile contact (Table 3).

The dynamic responses of the pile head such as velocity and settlement are recorded to control and verify the results of numerical analysis for comparison with measured results. The calculated results of the LWC cylindrical and tapered piles driving using the three-dimensional numerical analysis with those obtained from field tests are illustrated in Figs. 24 and 25. As observed, a satisfactory agreement exists between numerical predicted and measured field data.

After validation the numerical results next to field tests, the drivability of LWC piles in clayey and sandy soils was investigated by simulating the pile-soil system and the results are compared with CC piles. Numerical analysis of pile driving for non-uniform cross-section of common concrete piles have been studied by Ghazavi and Tavasoli (2012, 2016). They have performed three-dimensional finite difference analysis for geometry effects on pile driving

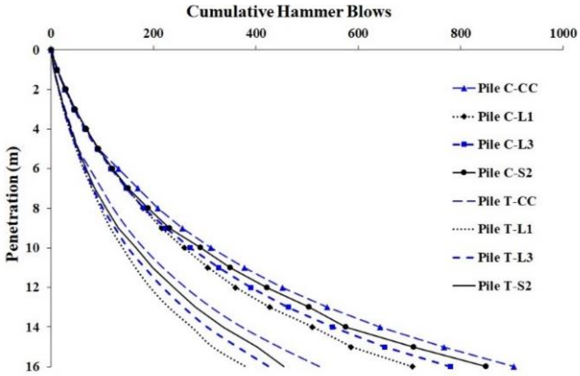


Fig. 26 Cumulative hammer blows for cylindrical and tapered piles with different concrete properties

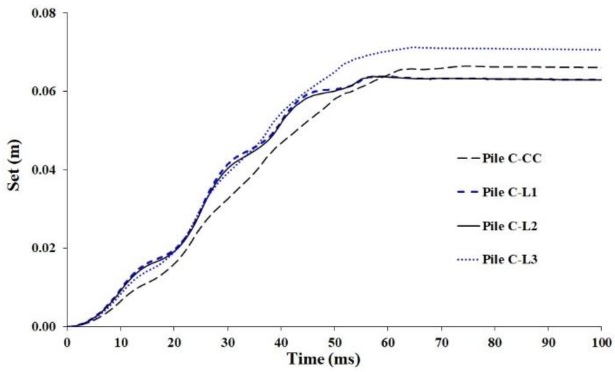


Fig. 27 Settlements of Pile C with different LWC-L and CC properties in clay

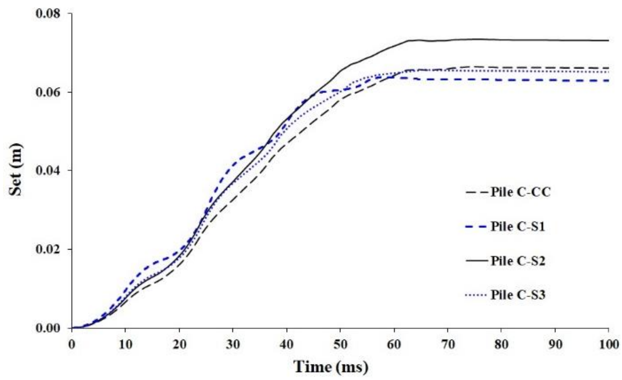


Fig. 28 Settlements of Pile C with different LWC-S and CC properties in clay

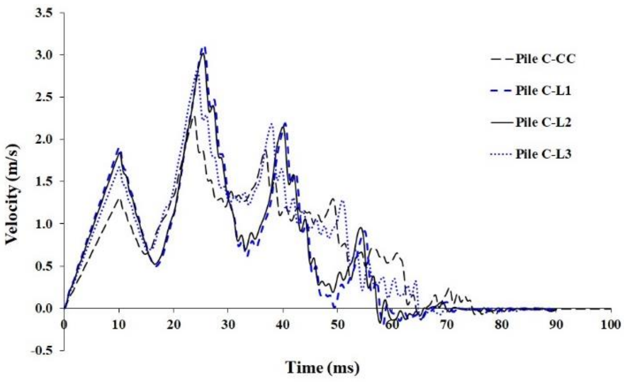


Fig. 29 Velocities of Pile C with different LWC-L and CC properties in clay

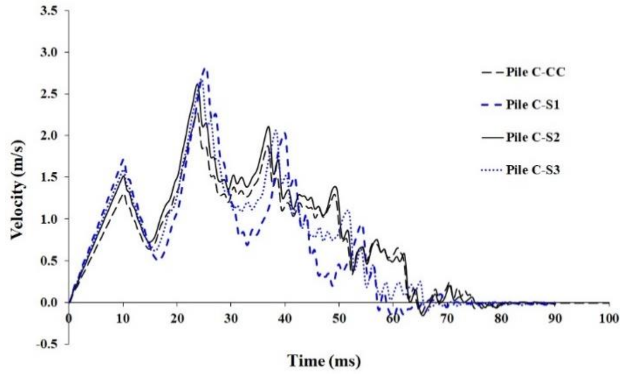


Fig. 30 Velocities of Pile C with different LWC-S and CC properties in clay

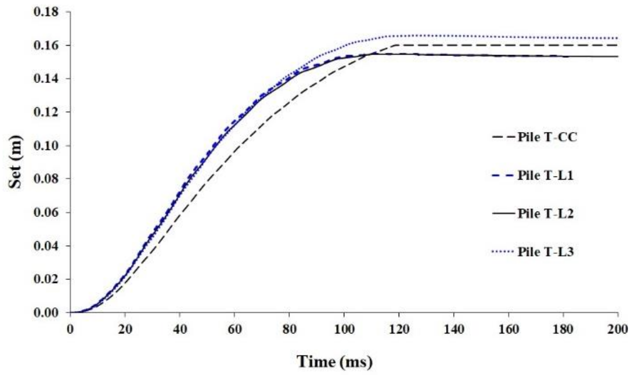


Fig. 31 Settlements of Pile T with different LWC-L and CC properties in clay

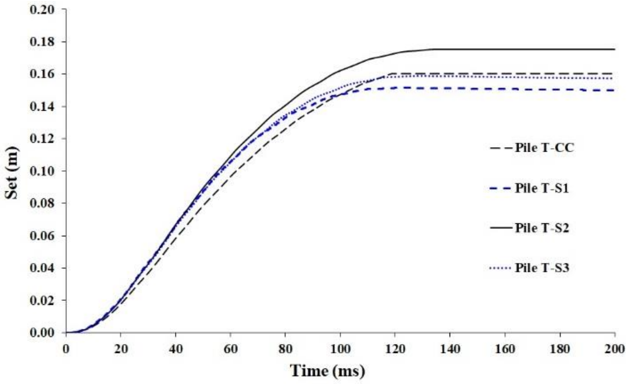


Fig. 32 Settlements of Pile T with different LWC-S and CC properties in clay

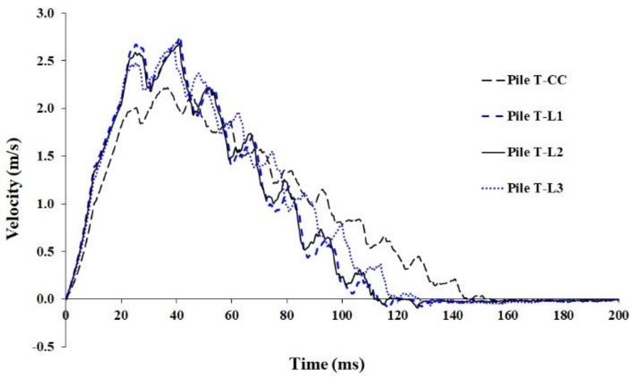


Fig. 33 Velocities of Pile T with different LWC-L and CC properties in clay

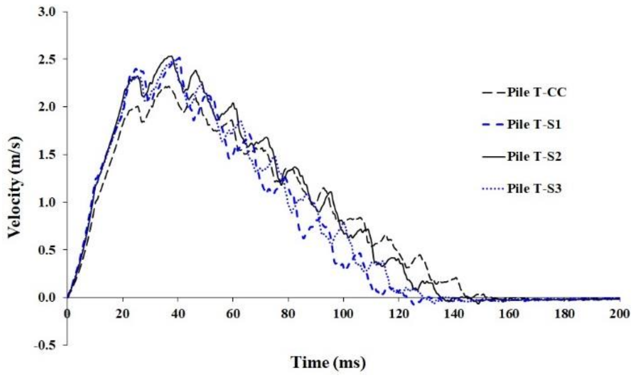


Fig. 34 Velocities of Pile T with different LWC-S and CC properties in clay

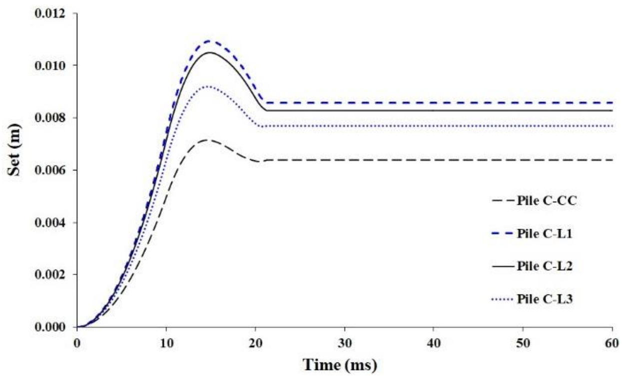


Fig. 35 Settlements of Pile C with different LWC-L and CC properties in sand

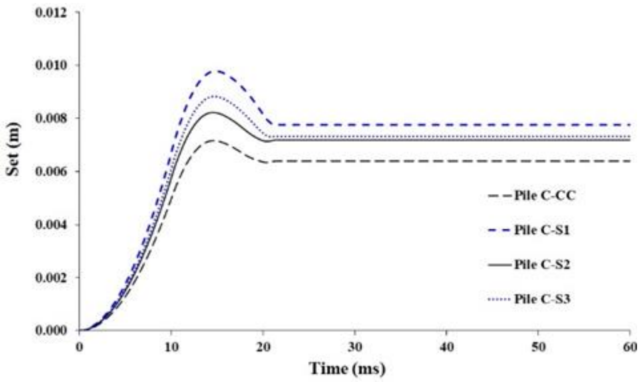


Fig. 36 Settlements of Pile C with different LWC-S and CC properties in sand

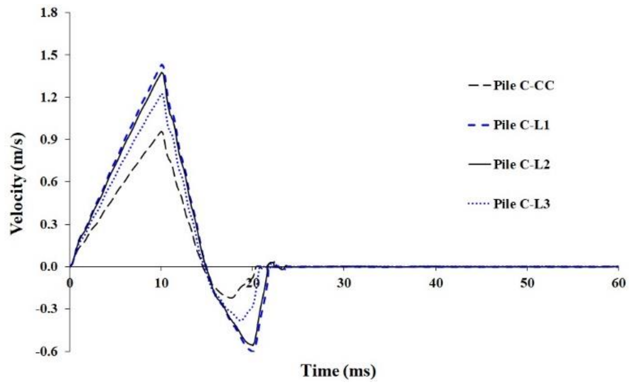


Fig. 37 Velocities of Pile C with different LWC-L and CC properties in sand

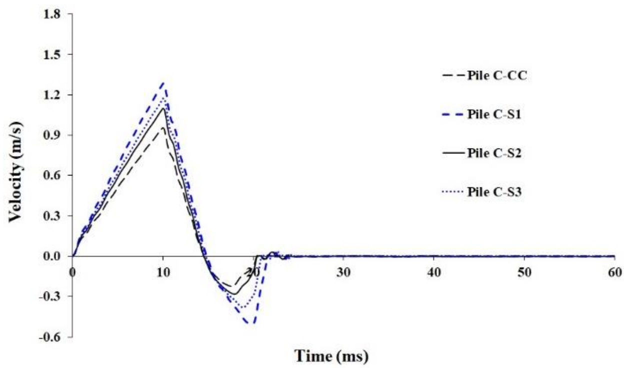


Fig. 38 Velocities of Pile C with different LWC-C and CC properties in sand

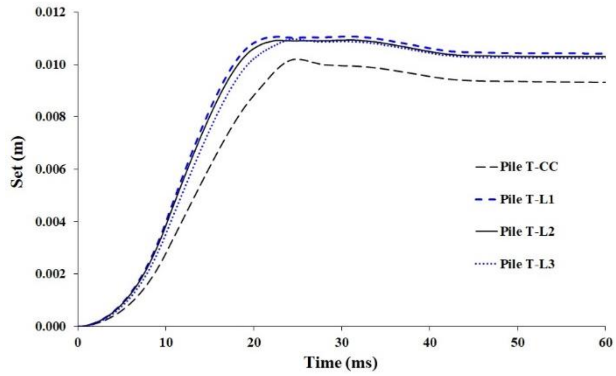


Fig. 39 Settlements of Pile T with different LWC-L and CC properties in sand

response and concluded that tapered and partially tapered piles offer better drivability performance than cylindrical piles. In this paper, it is assumed that the pile length is 16 m with the same volume. The properties and geometries of piles, boundary and initial conditions, hammer force function and soil constitutive models were described in details by Ghazavi and Tavasoli (2012). Pile T was non-uniform cross-section with 68 cm and 7 cm diameter at the top and toe. Pile C was cylindrical with 41 cm diameter (Fig. 23). Piles were installed to fully embedded length by using a hammer blow imported as a force function subjected at the top of pile. The pile and soil parameters were respectively illustrated in Tables 4 and 5. The lightweight concrete are divided to L and S types which respectively indicates the concrete mixture with Leca and Scoria aggregates.

The cumulative hammer blow counts versus the penetration depth were indicated in Fig. 26 for cylindrical and tapered piles with different concrete properties. As mentioned before, the field testing results showed that the tapered piles were penetrated with less hammer blows than the cylindrical one and also, the CC pile required more number of blows than LWC piles. By comparing the results, it is found that C-CC, T-CC, C-L3 and T-L3 piles require 904, 534, 780 and 426 hammer impacts respectively to penetrate to a fully embedded depth and tapered piles were installed in soil with 50% fewer number of blows. Also, for LWC piles, hammer blow counts decrease to about 15-20% in comparison with common concrete piles.

The piles head settlement and velocity in clayey soil

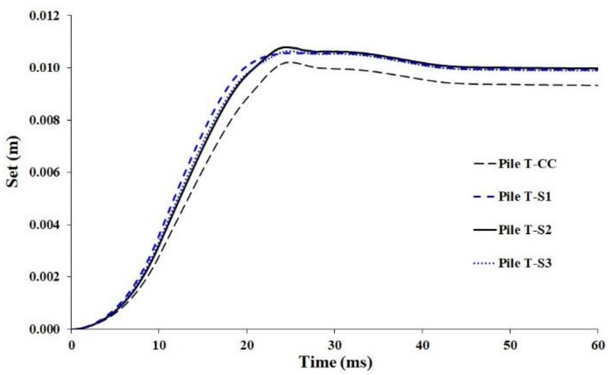


Fig. 40 Settlements of Pile T with different LWC-S and CC properties in sand

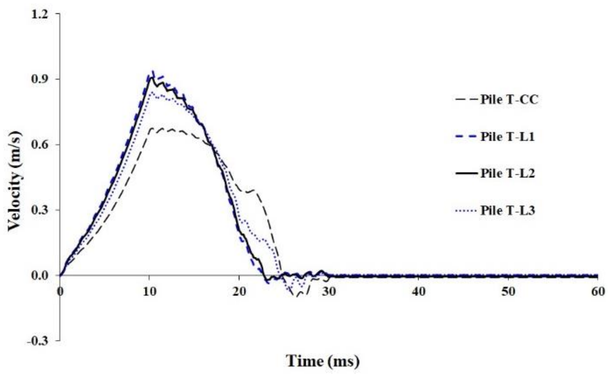


Fig. 41 Velocities of Pile T with different LWC-L and CC properties in sand

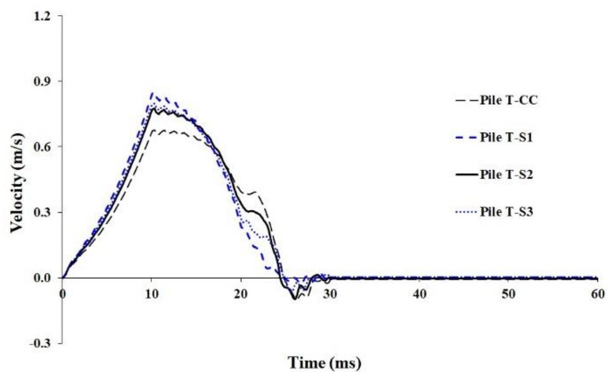


Fig. 42Velocities of Pile T with different LWC-S and CC properties in sand

were calculated and presented in Figs. 27 to 34 for the different types of LWC with Leca and Scoria. Based on obtained results and signal matching for LWC piles, the residual settlements and velocities of LWC piles in both different geometry had approximately similar and up to 20% better behavior and performance than CC piles, as expected. Therefore, LWC piles with appropriate ratio between elastic modulus and mass density had a better performance which affected the pile driving performance and economy.

Figs. 35 to 42 indicate the pile settlements and velocities driven in sand. As shown, Pile C has less settlement and velocity than Pile T, and also residual settlements of LWC piles are 15 to 40% more than CC piles. Therefore, better performance is expected from the drivability of LWC piles. Consequently, by comparing the behavior of concrete piles in clay and sandy soils, it is concluded that LWC piles can conveniently penetrate the soil. The reduction of the density of the pile material and increase the pile driving efficiency will eventually require less energy to install the piles and will be very safe and economic.

5. Conclusions

The drivability of tapered and cylindrical piles made of lightweight and common concrete was studied by performing field tests and numerical analyses. The signal-matching and dynamic responses of elastic rods were analyzed using FLAC3D. The LWC mixtures and parameters used as input data were obtained from laboratory tests to investigate the influence of the concrete properties and pile shape on drivability of LWC piles. The following concluding remarks may be cited:

• The measured results of full-scale driving tests on piles with different geometries indicate that tapered piles have a better performance than cylindrical piles. The cylindrical pile requires more number of blows than tapered piles to reach the same final penetration depth and also LWC piles require less number of blows than CC piles. Therefore, the LWC piles can be installed more rapidly and safely into the ground with higher efficiency.

• With signal matching analyses, the LWC piles with greater velocity than CC piles have better performance during pile driving.

• The driving efficiency of LWC piles in soil is better than common concrete pile. It is observed that T-LWC pile had more settlement and velocity in compared with C-LWC pile. The results indicate that the velocity and settlement increase up to 40%, depending on the ratio of elastic modulus and mass density.

• The application of LWC tapered piles have more and acceptable efficiency in pile driving procedure, improving the safety and durability of piles under hammer impacts.

In general, the LWC piles with appropriate mixture design and ratio between elastic modulus and mass density have better performance in pile driving compared to piles made of common concrete, since LWC piles have rapid penetration, are more economical and preserve energy saving.

Acknowledgments

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