

# Analysis on inclined or rounded tip piles using 3D printing technology and FE analysis

Jaehong Kim<sup>1</sup>, Junyoung Ko<sup>2</sup> and Dohyun Kim<sup>\*3</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, Dongshin University, Naju 58245, Korea

<sup>2</sup>Department of Civil Engineering, Chungnam National University, Daejeon 34134, Korea

<sup>3</sup>Department of Civil and Environmental Engineering, Hanbat National University, Daejeon 34158, Korea

(Received November 28, 2022, Revised March 5, 2023, Accepted March 7, 2023)

**Abstract.** To test the effect of various pile tip shape series of model scale loading tests were carried out on test piles with special pile tips. Special pile tips were made using the 3D printer and were attached to the bottom end of the test pile for loading tests. The pile tips were made to have 30°, 45°, 60° inclined tips, as well as a rounded tip. The main objective of the test was to observe the effect of various pile tip shapes on settlement and penetrability of the pile. Moreover, a numerical model simulating the pile loading test carried out in this study was established and verified based on the loading test results. From this, the stress concentration around the pile tip was investigated. This will allow us to analyze the decrease of stress concentration around the pile tip which is the main cause of the pile tip damage during pile installation. However, modifying the pile tip shape will eventually increase the settlement of the pile. By estimating the degree of increase in pile settlement, the viability and the efficiency of the pile shape modification was judged. In addition, case studies on the effect of different pile tip shape and ground conditions on pile settlement and stress dispersion was conducted.

**Keywords:** 3D printing; driven pile; load-settlement curve; pile damage (integrity); pile drivability; pile tip bearing

## 1. Introduction

The pile foundation has been the major source of stability for various types of social infrastructures. Its main purpose is to support the structures by transferring the load to a more viable ground condition, such as bedrocks beneath the surface. For this reason, the focus on studying and improving the piling method, to date, was solely on structural stability and bearing capacity. However, since the majority of the world population is living in urban areas (about 56% worldwide, and over 90% in Korea), most of the recent construction projects are also being carried out in urban areas as well (Korea Land and Geospatial Informatix Corporation 2022). Under this worldwide trend, piling now can not only focus on stability and bearing capacity – it is necessary to deal with problems involving of nearby structures and residences (Lee *et al.* 2016, Kim and Jeong 2021).

The most widely and frequently used piling method is the driven pile. It drives the pile into the ground by actually hammering the pile head. The driving energy which hammers the pile into the ground is transferred to pile bearing capacity, supporting the upper structure. The biggest advantages of using driven piles are that they have a relatively simple installation procedure and mobilizes high skin friction along the pile shaft as well as maximum pile tip bearing capacity (Gavin and Lahane 2003). The

disadvantage in using driven piles, and the biggest obstacle in applying driven piles in urban construction projects, is that it induces excessive vibration and noise which causes negative effect on nearby structures, buildings and residences.

Recently, the use of state-of-the-art technology, including 3D printing, in the field of geotechnical and foundation engineering has been widely studied and searched (Takemura *et al.* 2019). There were some meaningful movements in some academic advancement in the field of tunneling engineering, studying the changes in permeability of soil / rocks and gathering resources such as oil-sands (Hodder *et al.* 2018, Song *et al.* 2018, Deisman *et al.* 2019). However, most of the projects related to pile foundations were about using 3D printers for simple and fast manufacturing of the piles and mainly focuses on the application at the field rather than academic research (Hoffmann *et al.* 2021).

In this study, a model scale field test was carried out to investigate the concentration of the stress during driven pile installation and how the pile drivability are affected by various shapes of the pile tip. The test pile was prepared by attaching a steel rod to a special pile tip – with various shapes and angles – made by using a 3D printer. Through series of loading test, the difference in settlement was measured accordance with the different pile tip shape. Moreover, to observe the changes in stress concentration degree and pattern at the pile tip during penetration, a finite element analysis was conducted. Through this, the effect of modifying the pile tip shape in reducing nuisance during pile driving process was studied as well as serve as a framework in preventing pile tip damage caused by stress concentration.

\*Corresponding author, Professor  
E-mail: geokim@hanbat.ac.kr

## 2. Issues regarding driven piles

Pile foundation is considered the most effective method in supporting structures from small scale residential housing to massive industrial manufacturing plants while minimizing the settlement under axial loading. Among various piling methods, the driven pile is the most widely and frequently used method. Compared to other conventional piling methods, such as drilled-shafts or prebored and precast piles, driven piles are relatively easy to install due to simple installation procedure, driving (or hammering) the pile into the ground (Kim *et al.* 2020, Jeong *et al.* 2021). The main source of support of the driven pile is mobilized when the pile is being driven into a suitable bearing layer beneath the surface (Fig. 1). The harder the bearing layer it requires more driving energy to properly install the pile, which transfers to higher bearing capacity. So, to secure high bearing capacity, in most cases high driving energy is applied on the pile head.

However, recent construction planning is not only about the support and bearing capacity. It is becoming more aware of the effects it is causing to nearby structures, buildings and residences since more and more construction projects are taking place where the population is concentrated – the urban areas. In this case, the application of the driven pile as a main foundation method may not be suitable since it causes excessive noise and vibration during pile driving. The vibration may cause negative effect on nearby structures and buildings, as well as underground infrastructures including powerlines, water pipes or tunnels. The noise can lead to lawsuits filed against the construction project, which may increase unnecessary cost in the project.

To deal with this limitation, studies and efforts to improve the pile driving process have been carried out. Nonetheless, no viable option to reduce noise and vibration was available except for lowering the driving energy, which was not acceptable in actual engineering practice since the driving energy is directly related to the bearing capacity of the pile upper structure within the allowable settlement.

Another issue associated with driven piles are the possible damages on pile structures during driving. As mentioned above, the driving energy is the source of the bearing capacity. But while the pile penetrates the soil or sometimes rock, the driving energy reflects off the hard soil (rock) and cause damage on the pile, threatening the integrity of the pile structure. From this, it is not a rare coincidence to observe an edge of a pile tip damaged. These damages can lower the performance of the pile and threaten the structural stability of the structure, resulting in lower bearing capacity. However, the effort in increasing the drivability of the pile can be also considered as an increase in pile settlement under loading. For this reason, the effort to improve the drivability of the pile may yield in excessive settlement, which can contradict with the main role of the pile, which is to limit excess settlement and support the upper structure (Sajjadi *et al.* 2016, Kumara *et al.* 2016).

Although the driven pile has numerous advantages and can be used in various projects and occasions, the main disadvantages mentioned above – the nuisance during pile driving, issues on pile drivability and integrity – are limiting its wider application.

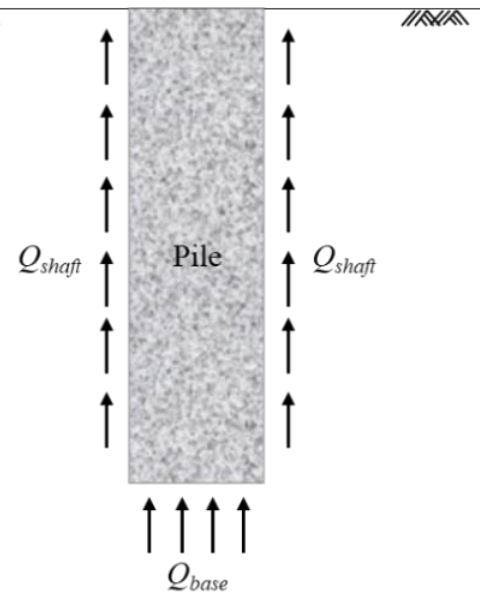


Fig. 1 Schematic of driven pile

## 3. Field test

Due to the fact that piles actually used in sites are usually massive in size experiments, studies and efforts to improve the piling method can be financially and physically challenging. Especially, when the test pile needs a custom made special shaped pile tip, the cost for the experiment preparation and test pile manufacturing will be exceptionally high. So, in this study, pile tips with various shape, size and angle were customized through digital modelling and made using the 3D printer (Model: *M-Flex Ex-One*). The customized pile tips were attached to a steel rod which served as a model scale test pile (Song *et al.* 2018).

### 3.1 3D printed pile tips

The effect of different pile tips with various shape, size and angle was investigated by using a customized pile tips made from a 3D printer, as shown in Fig. 2 (schematic of the half section of the actual pile tip). These also represent the numerical modelling of the test piles for the numerical analysis which will be discussed later in this paper. The material used in printing the pile tip was hard silicon. To secure high quality of the sample (25 MPa under uniaxial compression test), it was printed with layer thickness of 0.1 mm on the average speed of 10 mm/sec. These pile tips were attached to a steel rod with 10 cm diameter. The pile tips were customized to have an angle of 30°, 45°, 60° and a round tip. The diameter was also modified to 0 (point), 2, 4, 6 and 8 cm. As a default, a sample resembling a normal pile tip (90° angled edge and 10cm diameter) was also prepared.

### 3.2 Test preparation

Model scale loading test was carried out on a simplified

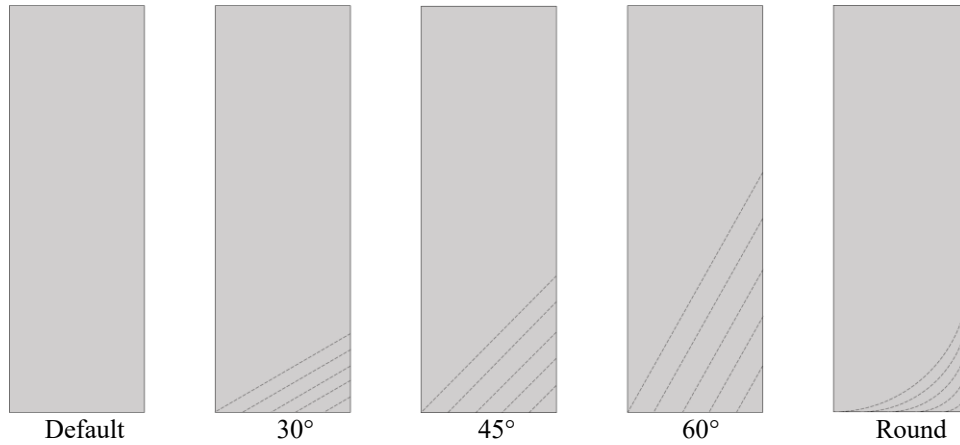


Fig. 2 Schematic of the 3D printed pile tips (diameter = 0, 2, 4, 6, 8 cm) (half section)

Table 1 SPT N-value at pile tip

Soil type	SPT N-value
Dense sand	25/30
Weathered rock	50/15
Soft Rock	50/3

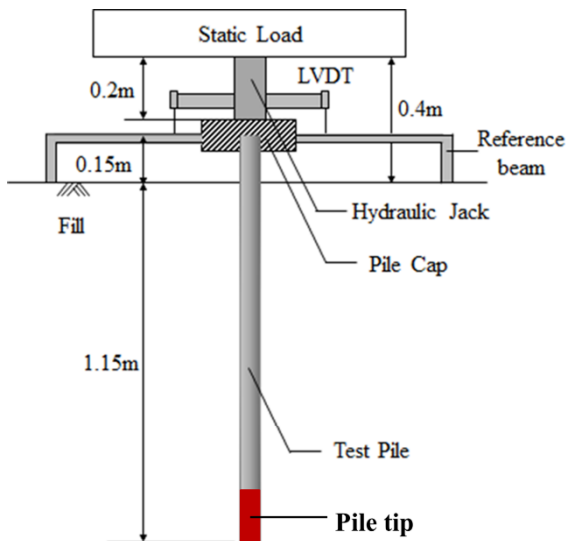


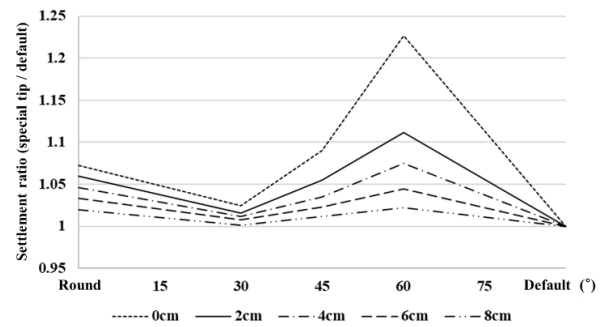
Fig. 3 Loading system and test preparation

loading system shown in Fig. 3. Static load is applied on the head of the test pile with the different length depending on the soil condition at the pile tip. The location of the pile tip was set to be placed under on a dense sand, weathered rock or soft rock condition, based on the SPT N- value. The SPT N-value at the pile tip location is summarized in Table 1. Total of 61 cases of loading test was carried out.

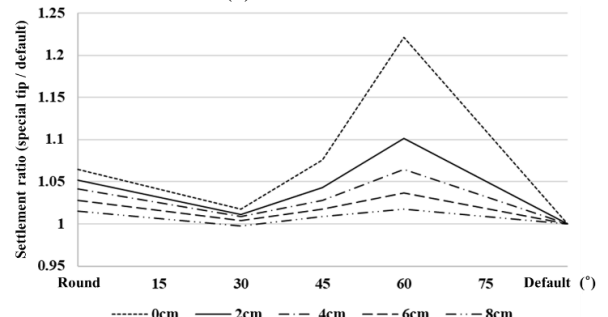
### 3.3 Test procedure

The model scale loading test was carried out on a test pile which is prepared by assembling a steel rod and the 3D printed pile tips. Since the main objective of the test is to investigate the relative difference in settlement associated with different pile tip condition, the test was planned to

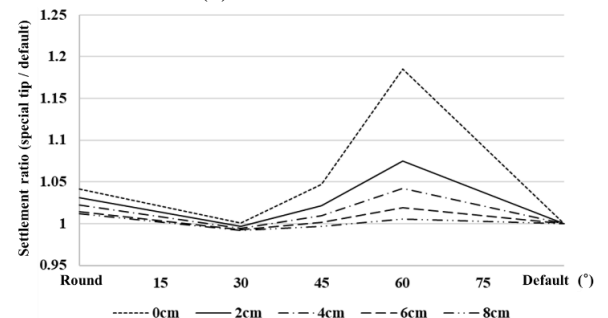
simulate very simple procedure of a loading test. The measurement of the pile settlement was obtained under constant loading of 100 kN over 20-minute period for all the cases (Cho *et al.* 2004). The measured settlements were normalized by the settlement obtained by a loading test done on a conventional pile tip shape.



(a) Dense sand



(b) Weathered rock



(c) Soft rock

Fig. 4 field test results (settlements, normalized)

Table 2 Field test results (settlement, normalized with the measurements from default pile tip)

Pile tip angle	Dense sand	Weathered rock	Soft rock
Pile tip diameter: 0 cm			
Round	1.0727	1.0649	1.0417
30°	1.0245	1.0173	1.0009
45°	1.0902	1.0758	1.0474
60°	1.2266	1.2208	1.1853
Pile tip diameter: 2 cm			
Round	1.0594	1.0519	1.0313
30°	1.0161	1.0108	0.9964
45°	1.0545	1.0433	1.0218
60°	1.1112	1.1017	1.0748
Pile tip diameter: 4 cm			
Round	1.0462	1.0411	1.0224
30°	1.0119	1.0087	0.9943
45°	1.0350	1.0281	1.0099
60°	1.0748	1.0649	1.0423
Pile tip diameter: 6 cm			
Round	1.0336	1.0281	1.0140
30°	1.0077	1.0043	0.9928
45°	1.0231	1.0173	1.0019
60°	1.0448	1.0368	1.0188
Pile tip diameter: 8 cm			
Round	1.0196	1.0152	1.0119
30°	1.0014	0.9978	0.9920
45°	1.0119	1.0087	0.9964
60°	1.0224	1.0173	1.0053

### 3.4 Test results

The field test results show that the change in the pile tip condition led to different settlement during loading. The field test results are shown in Fig. 4 and Table 2. Based on the results it was found that pile tips with modified tip angle showed increase in settlement under the identical loading. This tendency was shown in all soil conditions. Increase in settlement was largest in the case of the pile with 60° angle tip. Pile with 30° angle tip showed the least change in settlement, which in most cases was within the 1% range. The increase rate was in the order of 60°, round tip, 45° and 30°, showing an average of 8.3%, 3.7%, 3.1% and 0.5%, respectively.

The field test results also showed that as the pile tip diameter decreases, the settlement increases. It was expected that if the pile tip diameter was set to zero (sharp pile tip), the settlement will increase dramatically. However, if the results measured from the zero-diameter case was excluded, the increase in settlement was within the range of 10%.

If the results are analyzed based on the soil types, it was found that the dense sand condition was most effected by the changes in pile tip condition. The average changes in

settlement for dense sand, weathered rock and soft rock, was shown to be 4.9%, 4.3% and 2.5%, respectively.

## 4. Numerical analysis

Changes in pile tip shape and angle will alter the degree of stress concentration during pile driving. The changes in stress around the pile tip will affect how the pile material integrity will react. The changes in stress concentration around the pile tip was investigated through 3D finite element numerical analysis.

### 4.1 3D FE modelling

The primary focus of the finite element modelling was on simulating the model scale field loading test conducted in this study. A commercial package, ABAQUS 2019 (2019) was used for modelling and analyzing. Fig. 5 shows the schematic axisymmetric numerical model consisting of a single pile placed in a homogeneous soil along with the boundary conditions. The FE mesh was modelled to be finer around the pile to promote higher accuracy, but coarser away from the pile for shorter compute time. The pile was modelled as

Table 3 Soil properties for FE numerical analysis (Kim *et al.* 2020, Kim 2021)

Soil type	Unit weight (kN/m <sup>3</sup> )	Elastic modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Internal friction angle (°)
Dense sand	20	40	0.30	5	29
Weathered rock	21	200	0.30	50	32
Soft rock	25	6,000	0.24	1,000	35

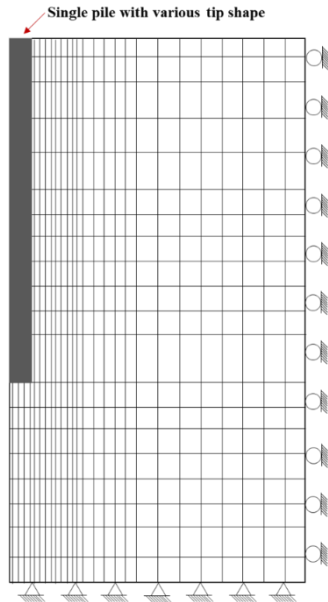


Fig. 5 Schematic of FE modelling and boundary conditions

a rigid material (Linear elastic), and the properties of the soil was based on a typical material property (Mohr-Coulomb model) of dense sand, weathered rock and soft rock, obtained from literature reviews, as shown in Table 3 (Kim 2018, Kim *et al.* 2020, Kim 2021). The shape, size and angle of the tip was modified between analysis to be identical to the field test conditions (total 61 cases). The total penetration length of the pile was simulated up to 50 cm.

#### 4.2 Remeshing method

To simulate the large deformation behavior of the driven pile, a large deformation method was applied in the numerical analysis (Ko and Jeong 2015). Large deformation behavior was considered in the computing process by restructuring the FE mesh every 1cm penetration of the pile (total of 50 steps). The new mesh inherits stress, settlement and other relevant information from the previous mesh. Fig. 6 shows the remeshing procedure applied in this study (Orazalin 2017, Orazalin and Whittle 2018, Kim 2021).

#### 4.3 Model verification

The finite element model was verified by comparing the numerical results with the measured data. Fig. 7 shows the measured and numerical results for the weathered rock case. Based on the comparison, it can be concluded that the

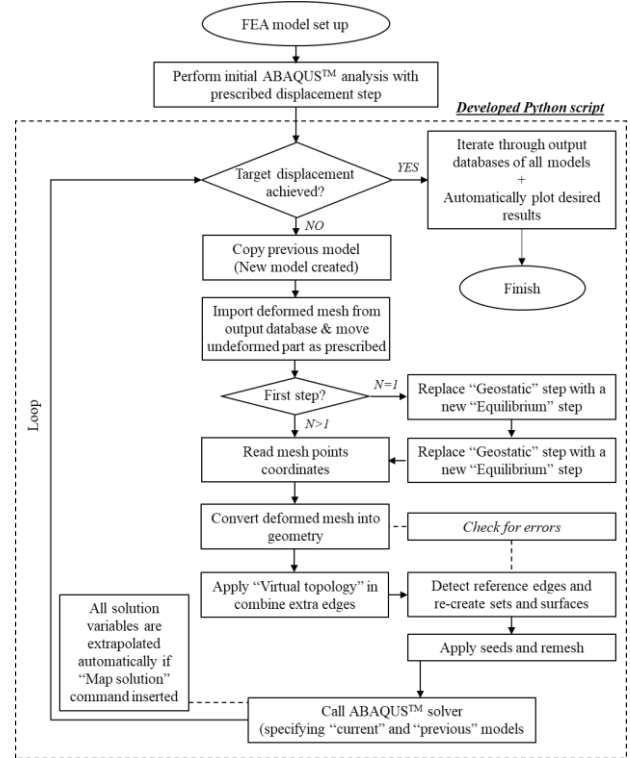


Fig. 6 Flow chart of the large deformation analysis using auto-remeshing process

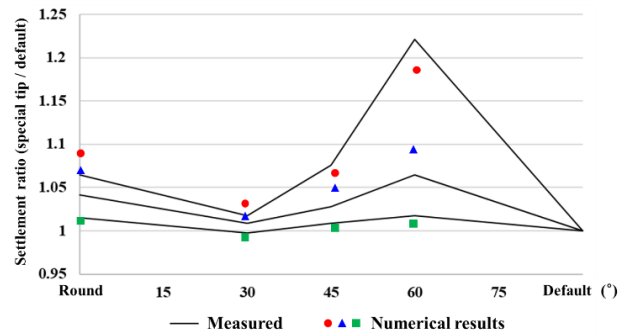


Fig. 7 Verification results of the numerical model

overall tendency in computing the changes in settlement difference was in good agreement for all soil conditions.

#### 4.4 Numerical results

The change in the stress concentration at the pile tip during driving was investigated through a series of finite element analysis. The results were analyzed by obtaining the maximum compression stress around the pile tip. The numerical results of all 60 cases are shown in Table 4 and

Table 4 Numerical results (maximum compression stress, normalized with the results from default pile tip)

Pile tip angle	Dense sand	Weathered rock	Soft rock	Max. Stress Location*
Pile tip diameter: 0 cm				
Round	0.3104	0.3070	0.2267	1
30°	0.6588	0.6413	0.4531	1
45°	1.0458	1.0370	0.6698	2
60°	2.4889	2.4468	1.9169	2
Pile tip diameter: 2 cm				
Round	0.2938	0.2923	0.2102	1
30°	0.7312	0.6561	0.4316	1
45°	0.5751	0.5479	0.3859	2
60°	0.9982	0.9801	0.6522	2
Pile tip diameter: 4 cm				
Round	0.3171	0.3156	0.2276	1
30°	0.7210	0.6613	0.4378	1
45°	0.5371	0.5011	0.3530	1(dense sand) / 2
60°	0.7660	0.7492	0.5111	2
Pile tip diameter: 6 cm				
Round	0.3652	0.3664	0.2633	1
30°	0.7219	0.6640	0.4410	1
45°	0.5353	0.5048	0.2852	1
60°	0.7660	0.7492	0.4990	2
Pile tip diameter: 8 cm				
Round	0.6065	0.6317	0.3735	1
30°	0.7049	0.6513	0.4375	1
45°	0.5813	0.5588	0.3714	1
60°	0.6485	0.7028	0.4835	2

\*Max. Stress Location refers to the location indicated in Fig. 8

Fig. 9. It was clear that the changes in the shape, size and the angle of the pile tip had a significant effect on the stress concentration degree and the pattern as well.

In case of the round shape pile tip, the degree of stress decreased significantly. In most cases, it showed 62 – 79% decrease in the maximum stress concentration at the pile tip during driving. The effect of the round tip was highest when the pile was driving through the soft rock condition. However, having a round shaped pile tip was least effective when the pile tip diameter was 8cm, and was driven in a weathered rock or dense sand.

Having a pile with 30° angle at the tip showed similar results with the rounded tip piles. It was more effective for soft rock condition in deducing the maximum stress, and less for weathered rock or dense sand condition. The degree of reduction was lower compared to the rounded tip pile. Overall, it showed about 27% - 56% decrease in maximum compression stress.

In case of a pile with 45° angle tip, the effects are in between the rounded tip and the 30° angle pile tip. The maximum stress is decreased by average of 43%. However, when the pile tip diameter is zero (sharp) and is under a

weathered rock or dense sand condition, the maximum stress increases. In this case, the maximum stress concentration was observed at the bottom tip of the pile (location 2 from Fig. 8), while for cases with rounded tip and 30° angle tip the maximum stress was observed at the side edge of the pile tip (location 1 from Fig. 8).

If a pile is modified to have a 60° angle tip, the maximum stress concentration will always be observed at the bottom of the pile tip (location 2 from Fig. 8). And when the pile tip is sharpened, the maximum stress concentration will increase significantly. Although the maximum stress concentration will dissolve as the pile tip diameter increase, it will show the least decrease among all the cases analyzed in this study.

The order of effectiveness in lowering the maximum stress concentration around the pile tip during driving was rounded tip, 45°, 30° and 60°. However, even though the drivability of the pile may be better when the tip diameter is smaller (sharper), having a sharp pile tip will increase the maximum stress concentration at the bottom part of the pile tip, which can cause chipping or damage of the pile tip, thus lowering the pile's structural integrity.



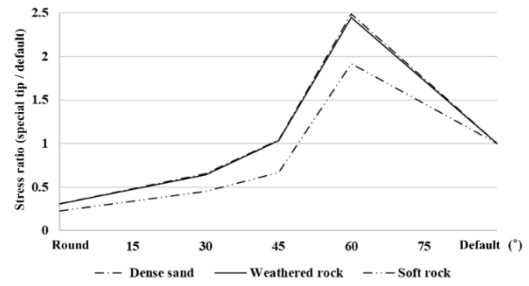
Fig. 8 Location of the maximum stress concentration

Modifying the pile tip shape, size and angle to decrease the maximum stress concentration around the pile tip was found to be most effective in soft rock condition. Even if the results of a sharp (zero-diameter) pile tip are excluded, modifying the pile tip will reduce the stress concentration by approximately 60% under the soft rock condition. Also, for the weathered rock and dense sand condition, the maximum stress concentration was reduced by at least 30% (zero-diameter case results excluded).

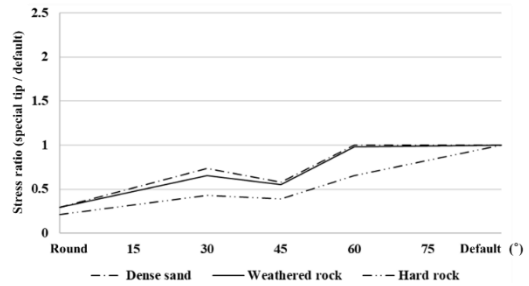
### 5. Conclusions

In this study, a series of model scale field test was carried out to observe the effect of the different pile tip condition – shapes, angles and diameters – on the pile settlement under static axial loading. Simultaneously, large deformation finite element numerical simulation was carried out to investigate the changes in stress patterns around the pile tip during driving. Main objective was to see whether the customizing of the pile tip was viable in improving the drivability as well as secure the structural integrity of the driven pile.

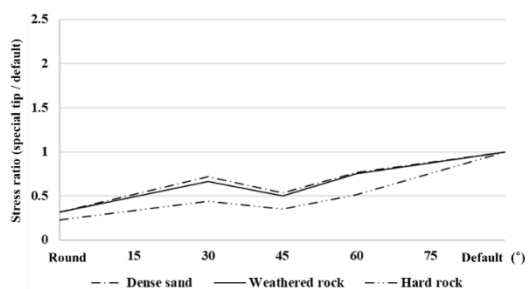
- The behavior of the test pile with customized pile tip, a 3D printed pile tip attached to a steel rod, was found to show higher settlement compared to a settlement of a test pile with conventional pile tip condition. Among various pile tip shape, the test cases with 60° angle pile tip showed highest degree of settlement increase. It was in the order of 60° > rounded tip > 45° > 30°, based on the average settlement increase.
- Among the three soil types, the dense sand was most affected, and the soft rock was least affected on average.
- If the cases with 0cm diameter, which is unlikely to be applied in the actual engineering practice, were excluded most of the cases showed approximately of 10% increase in settlement. The degree of settlement increase observed through field test can assumed as an acceptable range of increase, if it can lead to positive changes in other aspects of driven piles.



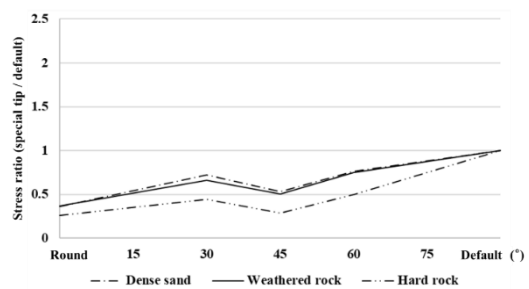
(a) Pile diameter: 0 cm



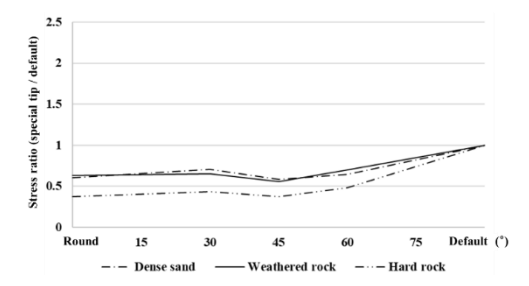
(b) Pile diameter: 2 cm



(c) Pile diameter: 4 cm



(d) Pile diameter: 6 cm



(e) Pile diameter: 8 cm

Fig. 9 Reduction of max. stress concentration at pile tip

- The changes in pile tip condition changed the degree of maximum stress concentration and the arrangements. In most cases, the maximum stress around the pile tip was found to be decreased significantly. The decrease in maximum stress around the pile tip during pile driving was most significant in the order of rounded tips, 45°, 30° and 60° in average.
- In case on the 60° pile tip, the average value of the maximum stress was found to increase. Based on a close look at the stress pattern, it was found that the location of the maximum stress shifted to the bottom of the pile tip, rather than the side edge of the pile tip, which was the case for normal pile tip and most of the cases computed. This pattern was also found in cases for 45° angle pile tips under weathered and soft rock condition.
- The changes in maximum stress concentration was found to be greater in the soft rock condition, followed by weathered rock and dense sand condition.

## 6. Remarks

The basis of this study was to observe the changes in pile behavior based on model scale field tests using 3D printed pile tip samples. However, the magnitude of the loading, scale effect and the pressure due to difference in pile socketed depth is significantly different from the actual engineering practice. For this reason, the results were presented as a ratio to the test results done on conventional pile shape, not the absolute (actual) measurements. These limitations will be dealt by conducting future studies under the centrifuge test conditions.

Despite the limitations mentioned above, based on the model scale field tests and numerical results, it can be concluded that the findings from this study can be applied in the actual engineering practice in some degree. For example, if the pile tip is modified to have a rounded shape or a 45° angle tip, the stress concentration around the pile tip during pile driving was decreased dramatically with an additional advantage in pile drivability. This may significantly reduce the possibilities in pile damage and secure the pile integrity. All this can be achieved without an excessive increase in settlement by pile tip modification.

However, there are some quality control conditions that must be met in applying the findings from this study.

First, the increase in drivability will require constant monitoring and checking the inclining of the pile during driving. If not, the pile may be battered and may not be able to perform based on design.

Also, the point of interest in securing the pile integrity should be shifted for some cases. Having an angle over 45° was found to shift the location within the pile where the maximum stress might concentrate.

Finally, the biggest difficulty it may face in actually applying the customized pile tip might be the financial issues. Mass manufacturing of a conventional normal shaped pile may cost less for each pile, due to the establishment of a production line. However, if the pile tip shape is to be modified and customized, the production cost of the pile will increase dramatically. Although in time the

production line of piles with certain angle of pile tip may be established, the initial cost in such establishment will be immense.

## References

- ABAQUS CAE (2019), *User's manual*, Dassault Systemes Simulia, Rhode Island, USA.
- Cho, C., Kim, H. and Kim, W. (2004), "Bearing capacity evaluation of the drilled shaft using small model test", *J. Korean Geotech. Soc.*, **20**(5), 117-126.
- Current state of urban planning: Statistical information report (2022), Korea Land and Geospatial Informatix Corporation; Jeonju, Republic of Korea.
- Deisman, N., Flottmann, T., Guo, Y., Hodder, K.J., Chalaturnyk, R.J. and Leonardi, C. (2019) "Using 3D printed synthetic rock for systematic evaluation of mechanical properties in coal", *Asian Pacific Unconventional Resources Technology Conference*, November 18–19, Brisbane, Queensland, Australia, SPE. <https://doi.org/10.15530/AP-URTEC-2019-198255>.
- Gavin, K.G. and Lahane, B.M. (2003), "The shaft capacity of pipe piles in sand", *Can. Geotech. J.*, **40**(1), 36-45. <https://doi.org/10.1139/t02-093>.
- Hodder, K.J., Nychka, J.A. and Chalaturnyk, R.J. (2018) "Process limitations of 3D printing model rock", *Prog. Addit. Manuf.*, **3**(3). <https://doi.org/10.1007/s40964-018-0042-6>.
- Hoffmann, M., Zarkiewicz, K., Zielinski, A., Skibicki, S. and Marchewka, L. (2021), "Foundations piles – A new feature for concrete 3D printers", *Materials*, **14**(10), <https://doi.org/10.3390/ma14102545>.
- Jeong, S., Kim, D. and Park, J. (2021), "Empirical bearing capacity formula for steel pipe prebored and precast piles based on field tests", *ASCE Int. J. Geomech.*, **21**(9). [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0002112](https://doi.org/10.1061/(ASCE)GM.1943-5622.0002112).
- Kim, D. (2018), "Proposed shaft resistance of prebored and precast pile using field loading test", Ph.D thesis, Yonsei University, Seoul, Republic of Korea.
- Kim, D. (2021), "Large deformation finite element analyses in TBM tunnel excavation: CEL and auto-remeshing approach", *Tunn. Undergr. Sp. Tech.*, **116**. <https://doi.org/10.1016/j.tust.2021.104081>.
- Kim, D. and Jeong, S. (2021), "Estimation of the excavation damage zone in TBM tunnel using large deformation FE analysis", *Geomech. Eng.*, **24**(4), 323-335. <https://doi.org/10.12989/gae.2021.24.4.323>.
- Kim, D., Jeong, S. and Park, J. (2020), "Analysis on shaft resistance of the steel pipe prebored and precast piles based on field load-transfer curves and finite element method", *Soil. Found.*, **60**, 478-495. <https://doi.org/10.1016/j.sandf.2020.03.011>.
- Ko, J. and Jeong, S. (2015), "Plugging effect of open-ended piles in sandy soil", *Can. Geotech. J.*, **52**, 535-547. [doi/10.1139/cgj-2014-0041](https://doi.org/10.1139/cgj-2014-0041).
- Kumara, J., Kurashina, T. and Kikuchi, Y. (2016), "Effects of pile geometry on bearing capacity of open-ended piles driven into sands", *Geomech. Eng.*, **11**(3), 385-400. <https://doi.org/10.12989/gae.2016.11.4.385>.
- Lee, C., Jeon, Y., Kim, S. and Park, I. (2016), "The influence of tunneling on the behavior of pre-existing piled foundations in weathered soil", *Geomech. Eng.*, **11**(4), 553-570. <https://doi.org/10.12989/gae.2016.11.4.553>.
- Orazalin, Z. (2017), "Analysis of large deformation offshore geotechnical problems in soft clay", Ph.D thesis, Massachusetts Institute of Technology, Cambridge MA, USA.
- Orazalin, Z. and Whittle, A. (2018), "Realistic numerical simulations of cone penetration with advanced soil models",

*Cone Penetration Testing 2018*, Delft, June.

- Sajjadi, S., Mirzaei, M., Nasab, A.F., Ghezelje, A., Tadayonfar, G. and Sarkardeh, H. (2016), "Effect of soil physical properties on infiltration rate", *Geomech. Eng.*, **10**(6), 727-736. <https://doi.org/10.12989/gae.2016.10.6.727>.
- Song, L., Jiang, Q., Shi, Y., Feng, X., Li, Y., Su, F. and Liu, C. (2018), "Feasibility investigation of 3D printing technology for geotechnical physical models: Study of tunnels", *Rock Mech. Rock Eng.*, **51**, 2617-2637. <https://doi.org/10.1007/s00603-018-1504-3>.
- Takemura, T., Isobe, Y., Okuzawa, K., Sanoki S., Shimo, M., Suzuki, K., Seiki, T., Nishimoto, S., Hamamoto, S. and Fujii, Y. (2019), "A review on application of 3D printer to geotechnical engineering", *Jpn. Geotech. J.*, **14**(4), <https://doi.org/10.3208/jgs.14.377>.