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Numerical analysis of offshore driven pipe pile refusal using *FLAC3D*

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1 INTRODUCTION

Fixed offshore platforms are supported by open-ended steel pipe piles in general. The drivability of the open-ended piles depends on the pile size, soil type and the hammer selected and is influenced significantly by the formation of soil plug inside the pile during driving, particularly in granular soils. Dynamic testing of the piles was carried out by installing strain gages and accelerometers at the pile top for most of the piles driven in the marine environment to control the pile drivability and also to confirm the pile design. Routinely, data from the dynamic testing of piles back analysed using the one-dimensional wave equation methods initially developed by Smith (1960), in which the pile driving is simulated using a number of masses attached to each other by elastic springs and dashpots. Signal matching analysis program CAPWAP (Case Pile Wave Analysis Program) developed by PDI (Pile Dynamics Inc.) is the most popular method to do the back analysis of the data from the dynamic testing. It is not possible to understand the behaviour of the soil and soil plug using the existing wave equation methods, however, using the continuum numerical model it is possible to understand the behaviour of the soil as well as soil resistance to driving.

Continuum method can be used for accurate analysis of the pile driving problem, as this method is based on a more realistic modelling of the actual physics of the pile driving than the wave equation (Nath, 1990). Stress waves generated in a pile due to hammer impact would propagate along its length and into the surrounding soil. The proportion of energy transmitted into each medium is dependent on the relative stiffness and pile-soil interace properties (Nath 1990, Murthy et al. 2019).

Analysis of the pile driving is extremely important when the pile driving is met with premature refusal. The present study is aimed at analysing the offshore driven pile met with refusal using the continuum method of numerical analysis. A continuum model in *FLAC3D* (Itasca 2017) (using axisymmetric model) for a solid driven pile has been performed by Masouleh & Fakharian (2008) to estimate the bearing capacity. During the pile driving operations, the plug formation in the soil can be understood by the sudden increase in the number of blows. However, the same during the numerical analyses can only be understood indirectly by the nature of stresses developed in the soil. The plug formation in the numerical analysis is indicated by increased soil stresses inside the pile compared to those in the outside soil. Further, the horizontal stresses increase rapidly compared to vertical stresses after the plug formation both inside and outside the pile (Murthy et al. 2019). The numerical analysis in the present study carried using signal matching analysis by matching the measured and computed data (velocity response of the hammer impact).

2 NUMERICAL MODELLING AND ANAYSIS

The study pile selected for the analysis is a steel pipe pile of 1.07 m outer diameter installed in the offshore South East Asia. The wall thickness of the pile was varied between 38.1 mm and 45 mm and a uniform wall thickness of 40 mm was used in the numerical model. The total length of the pile is 109 m, and planned target penetration was 60 m. However, the pile met with premature refusal at 41.5 m penetration below the seabed (more than 800 blows with no movement at hammer energy of about 675 kN-m) in the cemented sandstone layer. One hammer blow at the end of the pile driving was selected for the numerical analysis.

The numerical modelling of the driven pile in the *FLAC3D* is an iterative process and consists of two stages (Murthy et al. 2019). The first stage of the analysis is the initial equilibrium analysis. During this stage, the soil layers are allowed to reach the equilibrium under static conditions using overburden pressure and self-weight stresses, and then the resulting deformations were set to zero. The second stage of the analysis is dynamic analysis by applying the impact load of one selected hammer blow on top of the pile. The impact load applied is downward travelling wave force (Fdown, F_d) calculated from the measured force and velocity data from the pile instrumentation.

Pile is modelled as an elastic material, and the soil is modelled with an elastoplastic constitutive model with Mohr-Coulomb failure criterion. The soil around the pile is modelled as a square block of 16 m × 16 m × 70 m, as shown in Figure 1. The soil parameters and material properties of the soil are given in Table 1. The material properties of the soil for the first iteration of the signal matching analysis were arrived at based on common correlations (Bowles 1996) and the *FLAC3D* manual.

Table 1. Soil Properties and Material Properties.

Layer	Depth, m		Shear strength, kPa		Angle of internal friction, $ø^0$	Initial values of Young's Modulus, *E*, kPa	Final values of Young's Modulus, *E*, kPa	Poisson's ratio
	from	to	Top	bottom				
1	0	2			30	30,000.00	30,000.00	0.3
2	2	15	60	240		24,000 to 144,000	155,000.00	0.4
3*	15	33			35	60,000.00	100,000.00	0.3
4	33	36	360	360		300,000.00	360,000.00	0.4
5*	36	39			35	60,000.00	350,000.00	0.3
6**	39	42			40	100,000.00	500,000.00	0.4
7#	42	45	400	400		400,000.00	1,000,000	0.3
8**	45	47			40	100,000.00	500,000.00	0.3
9	47	56	440	440		400,000.00	400,000.00	0.4
10**	56	57			40	100,000.00	100,000.00	0.3
11	57	64	400	400		400,000.00	400,000.00	0.4
12	64	70			40	100,000.00	100,000.00	0.3

* Cemented sand layers
** Cemented sandstone layers
All the clay layers have the traces cemented clay pockets
Layer just below the pile, a combination of Cemented sandstone and very hard cemented clay

Interfaces between pile and soil along the shaft of the pile were provided on both inside as well as outside of the pipe pile to facilitate the relative displacement between the two. The interfaces were defined using the Mohr-Coulomb failure criterion. These interfaces along the shaft represent the skin friction capacity of the piles and also one interface provided at the bottom of the annular area of the pile to represent the end bearing force.

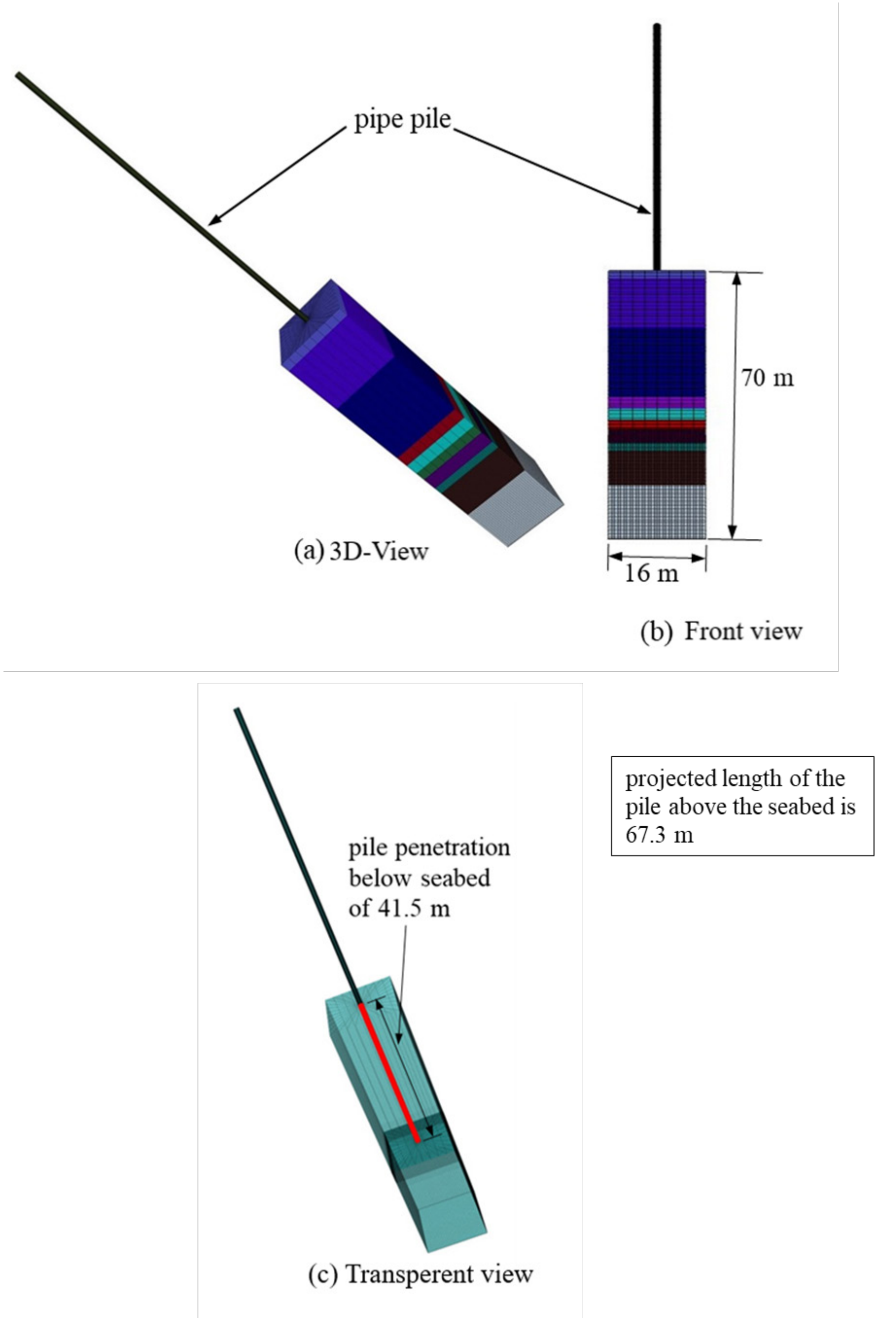

Figure 1. Pile-soil system considered in the numerical analysis of case study 1. (a) Isometric view, (b) Front view and (c) Transparent view with pile penetration and interfaces.

During the first stage of the analysis (static equilibrium analysis) of the system, fixity was applied at all the four sides of the model and the strength of the interface elements was set to zero. During the 2nd stage of the analysis (dynamic analysis), properties of the interface elements were defined for the first iteration as described in the *FLAC3D* manual. Viscous or quiet boundaries were created for the numerical system for the dynamic analysis.

Local damping of 2% (2% of π, which is 0.0628) was considered for the pile material. Local damping was also assigned for the soil inside the pile as well as soil below the pile tip. The analysis has been carried out initially with Rayleigh damping for the soil outside the pile and a relatively good match between the measured and computed velocity data has been achieved. However, to obtain better match towards the later part of the signal, artificial viscosity damping option available in *FLAC3D* has been used and resulted in a very good match between the measured and computed data (Figs. 2a & 2b). The reason for this may be because of the very hard driving and pile refusal observed in the field. The refusal had resulted in very high pile rebound during driving. Due to this high pile rebound, the amplitude of the hammer impact propagates along the pile for a longer duration before complete attenuation.

During the signal matching analysis, the material properties and the interface properties were changed until the computed velocity from the numerical analysis matched with the measured velocity data. The material properties considered in the first iteration, as well as the material properties derived at the end of the numerical analysis, are presented in Table 1. The final interface properties derived from the numerical analysis at the end of the signal matching analysis are presented in Table 2.

Table 2. Interface properties of the pile-soil system for pile (Final Iteration).

Interface element Number	Depth, m		Cohesion, C, kPa	Interface friction angle, δ^0	Normal Stiffness (kN/m^3)	Shear Stiffness (kN/m^3)
	from	to				
1	0	2	0	15	3.30×10^5	3.30×10^3
3	2	15	100	0	3.30×10^5	3.30×10^3
5	15	33	10	25	3.30×10^6	3.30×10^5
7	33	36	200	5	3.30×10^6	3.30×10^5
9	36	39	25	40	5.00×10^9	5.00×10^9
11	39	41.5	50	40	5.00×10^9	5.00×10^9
2	0	2	0	10	3.30×10^6	3.30×10^5
4	2	15	30	5	3.30×10^6	3.30×10^5
6	15	33	15	25	3.30×10^6	3.30×10^3
8	33	36	200	0	1.60×10^8	1.60×10^6
10	36	39	75	50	5.00×10^{11}	5.00×10^{12}
12	39	41.5	100	50	5.00×10^{11}	5.00×10^{12}
13	41.5	41.5	150	50	5.00×10^{11}	5.00×10^{12}

** Odd number represents outer interface and even number represents inner interface and element 13 represents interface at pile bottom*

3 RESULTS AND DISCUSSION

The soil stiffness (as represented by Elastic modulus of the soil) near the pile tip (just below the pile tip as well around the pile tip) was increased up to 7 times the initial values to obtain good match between the numerical predictions and measured values. This increase is due to the densification of the soil during the pile driving. In the present case of refusal, the soil stiffness increased for a distance of about 5 to 6 pile diameters above as well as below the pile tip due to very hard driving experienced during the pile installation (Table 1). The increase in the elastic modulus during the hammer impact is presented by Masouleh & Fakharian (2008), and Pinto & Granzina (2008). The strength properties of the inner and outer interfaces derived from the signal matching analysis represent the fraction of the total skin friction during the pile driving. This separation of the capacity of inner and outer interfaces is possible only with 3-dimensional continuum numerical models. The pile tip stresses calculated from the numerical analysis are higher than the stresses back-calculated from the CAPWAP analysis (Fig. 2c) which gives an accurate assessment of the pile tip condition during refusal pile driving in a cemented sandstone layer. The stresses in the soil just outside the pile along the pile shaft and inside the pile in the soil plug are presented in Figure 2d. It can be seen from the results presented, that both horizontal and vertical stresses are much higher on the inner side of the pile compared to the outside which indicates the severity of the plugging of the pile.

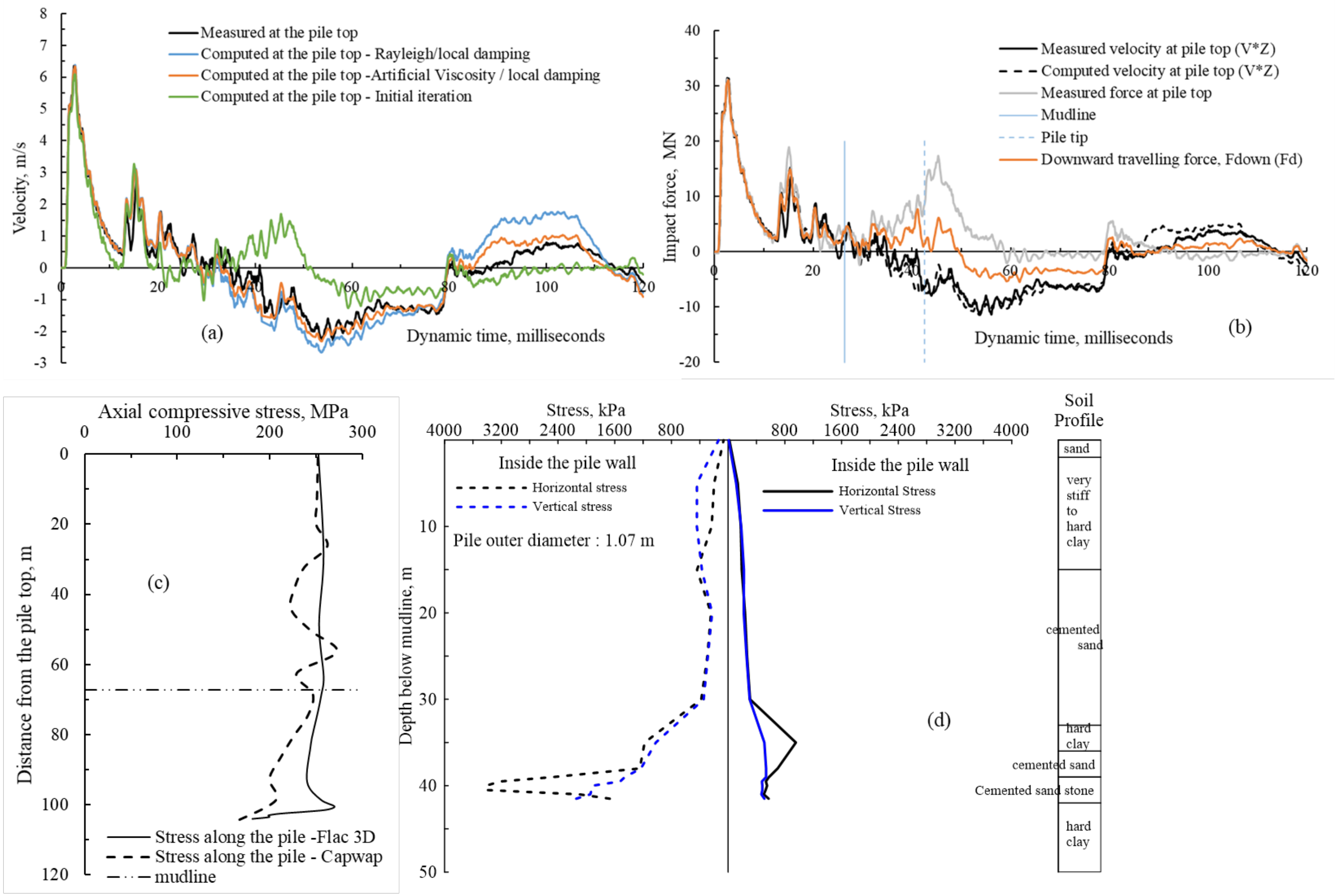

Figure 2. (a) Comparison of measured and computer hammer impact velocity, (b) Final results of the numerical analysis, (c) Comparison of the stress along the pile during driving and (d) Stresses in the soil and soil plug.

4 CONCLUSIONS

With 3D continuum numerical model of the pile driving,

- It is possible to model the behavior the soil plug and soil around the pile along with an accurate representation of the pile tip stresses.
- It is possible to incorporate the increased strength and stiffness of soil below the pile tip in the continuum numerical models for more accurate predictions.
- It is possible to approximately estimate the fraction of the internal skin friction out of the total skin friction.

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