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Use of Analytical model of Hammer Impact for Pile Drivability Study - a case study of pile foundation of Noetsu Bridge No. 3

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1. Introduction

The main objectives of drivability study are to establish a suitable hammer system for pile to be driven to required penetration without subjected to excessive driving stress and to provide guidance for penetration rate for known/assumed soil resistance. Drivability analysis requires modeling of hammer impact in order to provide input force wave at pile head as boundary condition for wave equation analysis of pile-soil system. This can be achieved by either numerical modeling of the hammer system (ram, cushion and anvil) or analytical solution of hammer impact at pile head. In contrast to numerical modeling of pile hammer system, analytical solution could produce accurate force-time response of actual hammer impact(Deeks *et al.*).

2. Test Description

The Noetsu Bridge No. 3 will be constructed on two abutments(A1 and A2) and four piers(P1 through P4). Open-ended steel pipe piles of varying wall thickness and length will be driven to required depth to support those abutments and piers. Geometrical and mechanical properties of each type are listed in Table 1. Soil investigation at the construction site revealed the presence of thick deposit of soft rock which has relatively uniform SPT value and shear strength at least upto 12 m depth. A total of 32 piles were driven at pier P1 and abutment A2 locations in 1995 and dynamic measurements (Force and velocity trace at pile head) for both end of initial driving and after some elapsed time were taken for all the piles. A large number of piles for the other locations will be driven and dynamically tested in April, 1996.

3. Verification of Analytical Model of Hammer Impact

For drivability prediction, an analytical modeling of hammer impact for ram/cushion/anvil system proposed by Deeks *et al.* (1993) was incorporated in a computer program KWAVE, which is based on characteristic solutions of stress-wave equation. Validity of prediction using the analytical model of hammer system is examined by the dynamic measurement data of piles at pier P1. Since the analytical modeling of hammer system used in prediction calculation represents drop hammer only, necessary reduction factor for input drop height in prediction analyses, is used to represent the diesel hammer used in the actual tests. The predicted results from the analytical model, the calculated(wave matching of dynamic signals) and the measured force time response at pile head for EID(end of initial driving) and redriving are shown in Fig. 1. Comparison between predicted, calculated and measured values of set per blow and rebound is shown in Table 2, together with the soil parameters and hammer system data used in prediction analyses. Set per blow, *S*, at EID obtained from the analytical model is quite comparable with measured one, while *S* at redriving from the analytical model predicts a little higher value.

4. Results of Pile Drivability Prediction

Pile drivability prediction of the piles for the remaining abutments and piers were also made to have a guidance for actual driving process. The soil parameters used in the verification analyses were again used in these prediction analyses, since the soil conditions at the construction site is relatively uniform. The hammer system includes ram mass of 3.5 ton, anvil mass 1.6 ton and cushion stiffness value set as 2×10^6 kN/m. For initial driving drop height of diesel hammer was selected as 1.4 m and corresponding input value for prediction analyses is set to 0.6m. For redriving, two drop heights 1.7m and 2.2m were selected with the corresponding input values of 1.0m and 1.65m respectively.

The results of the prediction analyses are summarized in Table 3. It is seen that with the selected hammer system and drop heights, the piles could be driven with satisfactory set per blow for both EID and redriving. Piles at A2 might not to be redriven with the hammer drop height of 2.2m, because it may overstresses the pile material. The results of energy calculation show that for a particular drop height, energy transfer to the pile is constant irrespective of pile geometry and soil resistance.

5. Conclusions

Pile drivability analyses were made for the piles to be driven for foundations of Noetsu bridge No. 3. The results obtained from the analytical modeling of hammer impact, may be useful in the sense that it could supply accurate and reliable information required in the design stage of pile driving.

6. References

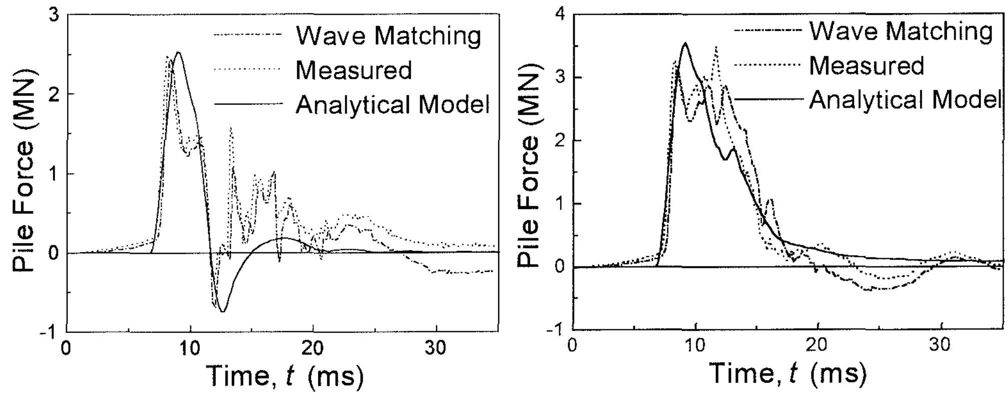
A. J. Deeks and M. F. Randolph. (1993): Analytical Modeling of Hammer Impact for Pile Driving, *Int. Jour. for Numerical and Analytical Methods in Geomechanics*. Vol. 17, pp. 279-302.

M. Hayashi, T. Matsumoto and Y. Futatsuka.(1996), Use of Dynamic Load Testing in the Design and Construction Control of Foundation Piles of Noetsu Bridge, Accepted for *5th Int. Conf. on Application of Stress-Wave Theory to Piles*, Orland, Florida, U.S.A.

Table 1 Specifications of piles

	E (MN/m²)	c (m/s)	L (m)	Pent^n (m)	Wall thick.(mm)	Out. Dia.(mm)	Inn. Dia.(mm)	Area (m²)
P1	2.06×10^5	5000	10.0	9.0	9	600	582	0.0167
P2	2.06×10^5	5000	11.5	11.0	12(4.5) / 9(7.0)	600	576/582	0.022/0.0167
P3	2.06×10^5	5000	16.5	16.0	14(5.5) / 9(11.0)	600	572/582	0.0257/0.0167
P4	2.06×10^5	5000	14.5	14.0	12(4.5) / 9(10.0)	600	576/582	0.022/0.0167
A2	2.06×10^5	5000	8.5	8.0	9	600	582	0.0167

Figure in parenthesis indicates length in meters of each pile section .



(a) End of Initial Driving (b) Redriving

Fig. 1 Comparison between prediction by analytical modeling, wave matching results and measured trace for pile top force response for piles at P1 location

Table 2 Soil parameters used and corresponding set per blow and rebound for piles at P1

Driving Condition	Depth of Soil (m)	τ_{max} kN/m²	Spring Constant MN/m³	Viscous Damping kN·s/m³	Comparison: Analytical model Set (mm)	Analytical model Rebound(mm)	Wave matching Set (mm)	Wave matching Rebound(mm)	Measured Set(mm)	Measured Rebound(mm)
EID	0 - 3	12.5	125.0	10.0	15.45	0.2	17.2	1.0	18.5	3.6
	3 >	25.0	100.0	15.0						
	Base	1500.0	937.5	40.0						
Redriving	0 - 3	140.0	121.4	20.0	5.35	2.5	3.7	3.9	3.7	9.8
	3 >	240.0	56.0	50.0						
	Base	31440.0	2860.0	80.0						

Table 3 Prediction results from analytical modeling of hammer impact for piles to be driven.

Pile Type	Driving Condition	Drop Height (m) Actual	Drop Height (m) Cal.	Prediction Set (mm)	Prediction Rebound(mm)	Max^m Stress MN/m²	Energy (kN·m) ENTHRU	Energy (kN·m) Transferred
P2	EID	1.4	0.6	12.9	0.3	136.0	19.3	16.0
		1.7	1.0	3.7	4.3	191.4	29.0	22.2
	Redriving	2.2	1.65	5.9	4.6	242.3	48.5	40.5
P3	EID	1.4	0.6	10.1	0.2	131.5	19.5	18.0
		1.7	1.0	2.8	4.9	183.0	30.4	22.0
	Redriving	2.2	1.65	3.9	6.2	232.5	50.6	38.5
P4	EID	1.4	0.6	11.5	0.2	136.0	19.3	17.5
		1.7	1.0	3.0	4.9	191.5	29.0	20.6
	Redriving	2.2	1.65	4.2	6.2	242.3	48.5	36.2
A2	EID	1.4	0.6	16.2	0.3	154.0	17.6	14.8
		1.7	1.0	5.7	2.7	231.2	27.0	23.0
	Redriving	2.2	1.65	8.9	2.9	278.5	46.3	42.0