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STEEL PILES DRIVING PROCEDURE AND RESULT ANALYSIS OF EXTRADOSED BRIDGE MAINLAND - PELJEŠAC

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Abstract

In order to meet the high requirements of marine environmental protection and Eurocodes, based on the actual construction conditions of deep water on site in Croatia, the extra-long steel pile foundation was adopted to Pelješac Bridge. At the meantime the corresponding extra-large scale pile driving barge had to be used to carried out during the construction. The pile bearing capacity was analyzed and checked by the actual measured PDA (Pile Driving Analyzer) data. The test results showed that the toe bearing capacity of driven piles had linear relationship with blow counts, and the penetration (displacement/blow) before the stoppage was inversely proportional to toe bearing capacity. In addition, the traditional empirical formula of long-term pile bearing capacity of driven piles was only suitable for the piles, which were shorter than 100m. The stoppage criteria of extra-long pile should concentrate on penetration firstly, while the pile design elevation was subsidiary factor. Therefore, the analysis of pile driving procedure and results could be considered as significant actual engineering reference for the coming works.

Keywords: driven piles, blow counts, penetration, long-term bearing capacity

1 Project Introduction

The extradosed cable-stayed Bridge Mainland - Pelješac is financed by EU fund and constructed by the international contractor China Road and Bridge Corporation (CRBC). This project was the largest infrastructure project under construction in Croatia at present. The bridge has the whole layout of 84 +108 +108 +189,5 + 5 x 285 +189,5 + 108 + 108 + 84 = 2404 m, and the total length of the bridge including abutments was 2440 m. There was total 10 piers located in the sea. Therefore, the corresponding 150 pieces of steel pipe piles were constructed in the deep sea.

2 Classification of pile foundation

Pile works was separated into two main types according to different categories of pile toe characteristics. One type was steel driven pile with stiffening pile shoes, which were embedded into hard rock and the upper 40m were filled with reinforced concrete, however, the other type was driven piles with concrete sockets instead of stiffening pile shoes stand on the hard rock, the pile inside and socket was drilled by drilling machine and filled with reinforced concrete. The longitudinal stiffeners were welded inside for improving the stability of steel tubular piles, and also enhancing the connection between steel tubular piles and concrete. The 2-meter-long pile shoes were made of steel S460NH with the wall thickness of 60

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mm. Additionally 8 pieces of stiffeners were set inside of pile shoes of the first type, so steel driven piles had larger compression areas than concrete-socketed piles, and the maximum allowable stress during the driving must be different. See Figure 1.

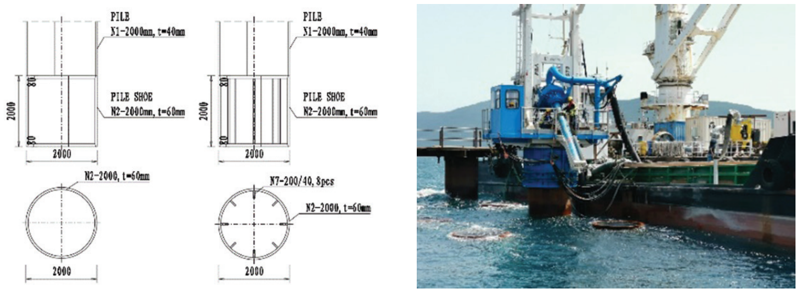

Figure 1 Pile classification and RCD drilling machine

3 Steel pile production and transport

The design lengths of piles ranged from 36 m to 130,6 m. The proportion of design length over 100m exceeds 70 %. If the extra-long steel pile was divided into two large segments for production, after that they were spliced in the air and welded on bridge site, it would lead to high risks of safety and quality. Firstly, the welders must enter inside from the 60-meter-high pile top. Secondly, in order to decrease the influence of wind and wave, the adopted platform and barges must be anchored on the sea as stable as in the workshop, in this case the straightness and concentricity of piles couldn't be ensured seriously according to EN 10219-2: 2006 Table 2 [1]. Thirdly, the manual welding quality on site couldn't meet the requirements of EXC4 B+, referring to Table 17 in EN 1090-2: 2008 [2]. As contractor's final determination the extra-long steel piles were entirely manufactured instead of connection on site. All of the extra-long steel piles were manufactured in China workshops, and then the cargo vessel took them to Croatia in six batches respectively. Since the contractor started the pile production until the completion of pile driving on site, the pile works period had been achieved and controlled efficiently within only 5 months.

Figure 2 Steel tubular piles storage at port and uploading to cargo vessel

4 Driving procedure and stoppage criteria

The mean water depth was 27,0 m on bridge site, the thickness of soil under seabed is between 30 m and 100 m, it was composed of soft clay, hard clay and gravel. The hard clay layer was started from 60 m deep and its negative skin friction was up to 300 kPa. The hard rock layer located below the hard clay. The strength of hard rock was about 80 MPa. After the com-

prehensive consideration, the driving barge was equipped with the hydraulic hammer finally, type IHC S800. The kinetic energy on hammer output was $E_{k,\ max}$ = 800 KJ, due to energy loss of system the real transmitted energy into the pile could be up to 85 or 90 % of the output $E_{k,}$. The maximum pile driving length by driving barge could be up to 133 m.
Dynamic monitoring was performed with equipment which corresponded to the standard ASTMD4 945-08 ‹Standard Test Method for High Strain Dynamic Testing of Deep Foundation›, for characteristic strikes at the end of the pile driving, CAP / WAP analysis was performed for each pile. Steel piles were driven in the accordance with the following procedures strictly,

a) Piles were lifted and positioned correctly by pile driving barge.
b) Piles sunk until stillness by self-weight of pile and hammer.
c) Started the hammer with 10 % of $E_{k,\ max}$ and recorded the blow counts.
d) Increasing 10 % of output energy E_k gradually, based on the actual penetration. The penetration was controlled around of 20 cm / 25 blows.
e) Stoppage for the installation of the Pile Driving Analysis (PDA) sensors, the last 20 m of the pile driving was monitored and the dynamic response was recorded.
f) Keeping on pile driving until final stoppage according to stoppage criteria. Meanwhile pile body and toe stresses were controlled under the maximum of the allowable stress.

Figure 3 Steel pile driving by large-scale driving barge

Before the final stoppage of hammer, the following pre-conditions should be taken into consideration comprehensively.

- Under full energy of hammer, in the range of the last 1,0 meter the average blow counts were more than 250 for each 25 cm (1 mm / blow)
- Penetration was reduced to 20 blows each 10 mm (0,5 mm / blow)
- The pile body stress was close to maximum allowable stress.
- Pile body and toe stresses by the dynamic monitoring met the requirements of PDA engineer.

In summary, the bearing capacity of the pile toe was the dominating factor of stoppage for the driven piles with stiffening pile shoes, and in the meanwhile design elevation of piles was stoppage criteria for the concrete-socketed steel driven piles.

5 Pile bearing capacity analysis

5.1 End driving results analysis (ED)

The following Figures 4 and 5 showed the relationship between the final penetration and the pile bearing capacity. The PDA equipment measured and recorded all the original driving data, which were from 45 concrete-socketed and 94 driven piles respectively. The most of two types of the piles had some points in common.

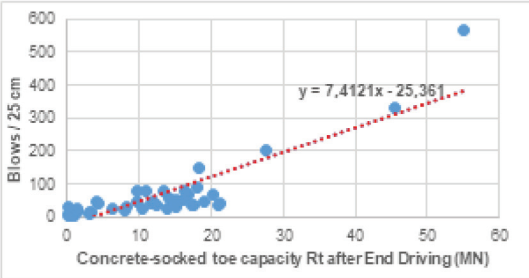

Figure 4 Concrete-socked pile curve

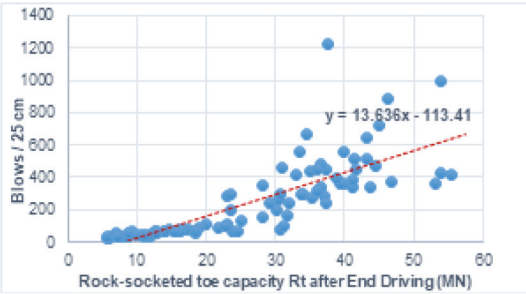

Figure 5 Driven pile curve

- Toe bearing capacity of vertical direction was directly linear proportional to blow counts of hammer.
- It shows inverse ratio of pile penetration (displacement per blow) and vertical bearing capacity.
- In comparison with concrete-socketed piles, the data of driven piles showed more discrete characteristics. And there were also some differences between the two types of piles.
- Steel driven riven piles had much higher measured toe bearing capacity than concrete-socketed piles.
- The final penetration of steel driven piles was quite smaller than concrete-socketed piles.

The reason of the mentioned differences was that the driven piles were mainly supported by hard rock directly, and the other type of piles was supported by skin friction and concrete socket together. In addition, the chart data was proved that it's consistent with the summary of stoppage criteria in previous chapter 4.

5.2 Re-Driving procedure (RD) and long-term pile bearing capacity

In order to check if the shaft resistance increased and meanwhile estimate how the growing trend for the final vertical bearing capacity will be. The 130,6-meter-long Pile No. TP7 as the chosen test pile was driven several times within one month. The RD tests were carried out after ED with a wait period as following orders:

1) Pile position was marked with total station by the surveyor on shore.
2) 5 blows with full energy $E_{k,\ ma}$.
3) Vertical settlement was recorded and reported to PDA engineer.
4) The mentioned procedure was repeated 3 times, in order to calculate the average value of skin resistance.

Based on the following data of TP7, the trend of final bearing capacity and soil setup effect could be analyzed (see Table 1):

- The skin friction $R_{s,act}$ around the pile increased much faster after initial driving.
- Within the first 2 days a rapid consolidation of the soil caused recovery by the shaft resistance.
- Although it is a long-term process of soil setup and friction increasing, over 90 % of the process were completed within 3 weeks after the initial driving.
- The activated part of toe bearing capacity is decreased step by step, due to the increasing effect of soil consolidation.

The measured maximum skin friction $R_{s,act}$ was in the range of 50 MN. However, it was only partially activated. The maximum activated friction was dominated by transmitted effective energy from hammer, so the more energy of hammer could be transmitted, the more skin friction could be activated.

Table 1 Test pile TP7 origal data of pile driving

Time	Days	Skin friction $R_{s,act}$ [MN]	Toe bearing capacity $R_{t,act}$ [MN]	Pile bearing capacity $R_{u,act}$ [MN]	Bearing capacity at superposition R_{u_sup} [MN]	Set [mm]
ED	0,001	6,6	**20,8**	27,4	27,4	5
1 hour	0,042	28,5	11,7	40,2	49,3	1,5
1 day	1,0	40,6	8,6	49,2	61,4	1
2 days	2,0	48,9	4,18	53,1	69,7	<1
4 days	4,0	51,0	2,5	53,6	71,8	<1
19 days	19,0	**53,5**	0,5	54,0	**74,3**	<1

In principle, when transmitted energy was not limited by driving equipment, the shaft friction and toe resistance could be activated fully. Therefore, the bearing capacity at this moment was regarded as superposition R_{u_sup}. It could be calculated approximately by the following formula (1)

$$R_{u\_sup} \geq R_{s,act} = R_{s,act} + R_{t,act} \tag{1}$$

The maximum activated toe bearing capacity $R_{t,act}$ = 20,8 MN was confirmed after initial driving, the activated skin friction $R_{t,act}$ was measured individually. As a result, the total pile bearing capacity after re-driving $R_{u,RD}$ was confirmed and meanwhile the maximum bearing capacity $R_{u,max}$ was more than $R_{u,19}$= 74,3 MN. But it was quite closer to bearing capacity at the superposition.

Up to now, Denver & Skov (1988) long term formula was best approximation of long-term pile capacity. The total bearing capacity followed a linear increase versus the log of the time elapsed after initial driving. As follows [3]

$$\frac{R_u}{R_0} = 1 + A\log\left(\frac{T}{T_o}\right) \tag{2}$$

Remark: R_u and R_0 are the whole pile bearing capacity corresponding to time T and T_0 respectively. T_0 is the reference time at start of log-linear capacity increase. A is dimensionless setup factor.

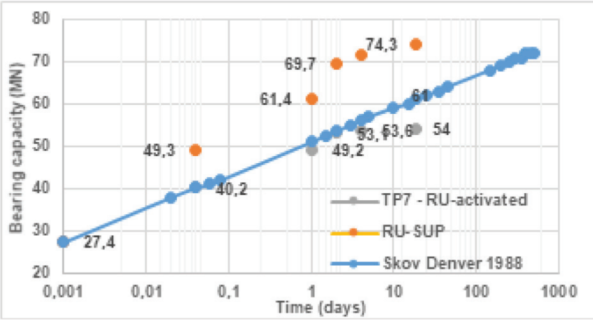

Figure 6 Log-linear long-term pile bearing capacity

Put the data of re-driving at the 0,001 and 0,042 day into above formula and get *A* was 0,288. As a result, the calculated bearing capacity of 19th day was 61,0 MN. But the measured $R_{u,19}$ was 54,0 MN. Therefore, the empirical formula for extra-long driven pile wasn't verified in this project. The main reason was the skin friction was partially activated, and the penetration after 1 hour was only 1,5 mm/blow.

6 Conclusion

The bearing capacity of driven piles was linear proportional to blow counts, and the penetration of the final stoppage was inverse proportional to bearing capacity. Because the pile cap entered under the water before final stoppage, the energy attenuation was deviation of around 10 % between the actual PDA measured energy and the initial output hammer energy. The traditional empirical formula for the bearing capacity of driven piles was only suitable for the length under 100 m. For the extra-long piles with the length over 100 m, the final stoppage criteria should follow the regulation of "Penetration mainly, Pile elevation supplementary"

Reference

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