Hybridnamic Rapid Load Tests for Cast-in-situ Piles in Sandy Gravel Soil

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Keywords: Rapid load test, Cast-in-situ pile, Shaft resistance, Sandy gravel soil

ABSTRACT: This paper presents results of three Hybridnamic rapid load tests for cast-in-situ piles with a diameter of 1.0m. The cast-in-situ piles were adopted as the foundations for Hokuriku-Shinkansen super express railway pier bridges at Toyama prefecture in Japan. The piles were designed to be installed to sandy gravel soil layer with N value of larger than 50. The embedded length into the bearing layer had to be more than 5m for fear that liquefaction under earthquake might reduce the pile capacities. Three Hybridnamic rapid load tests were carried out to indicate the total pile capacity and the shaft resistance of the sandy gravel soil. Three test sites, Imizu, Takaoka and Oyabe were chosen at different locations along the planned railway. The results of the pile load tests showed that load-displacement curves have behaviours of friction piles. The indicated shaft friction stress resulted to shorten the lengths of the working piles.

1 INTRODUCTION

Hokuriku-Shinkansen super express railway is under construction aiming at operation in 2015. The design of the cast-in-situ piles for the pier bridge of Hokuriku-Shinkansen built by about 13 km between Imizu and Oyabe in Toyama prefecture was carried out. The cast-in-situ-piles will be deeply embedded into the bearing layer of sandy gravel soil in consideration of the fall of the shaft friction resistance by liquefaction of shallow sand layer. Then, in order to indicate the shaft friction of the cast-in-situ piles in the sandy gravel bearing layer, the rapid pile loading tests named Hybridnamic tests were carried out on three test piles at different places respectively. A possibility of shortening the length of working piles was examined based on the result of the pile load tests. This paper reports these rapid load tests outlines, test results, and the evaluation of the shaft friction with reference to the papers of Yamazaki & Sugihara et al. (2009) and Yamazaki & Aoki et al. (2009).

2 SHAFT FRICTION OF CAST-IN-SITU PILE

The cast-in-situ piles for the pier bridges were designed that the embedded length into the sandy gravel layer had to be more than 5m. Shaft resistance, f of a cast-in-situ pile is prescribed to be calculated by f=5N kN/m^2 and the maximum value is limited to be 200kN/m^2 in Japanese design standards for railway structures. In a stiff soil layer where N value is larger than 40, a design pile length will become long.

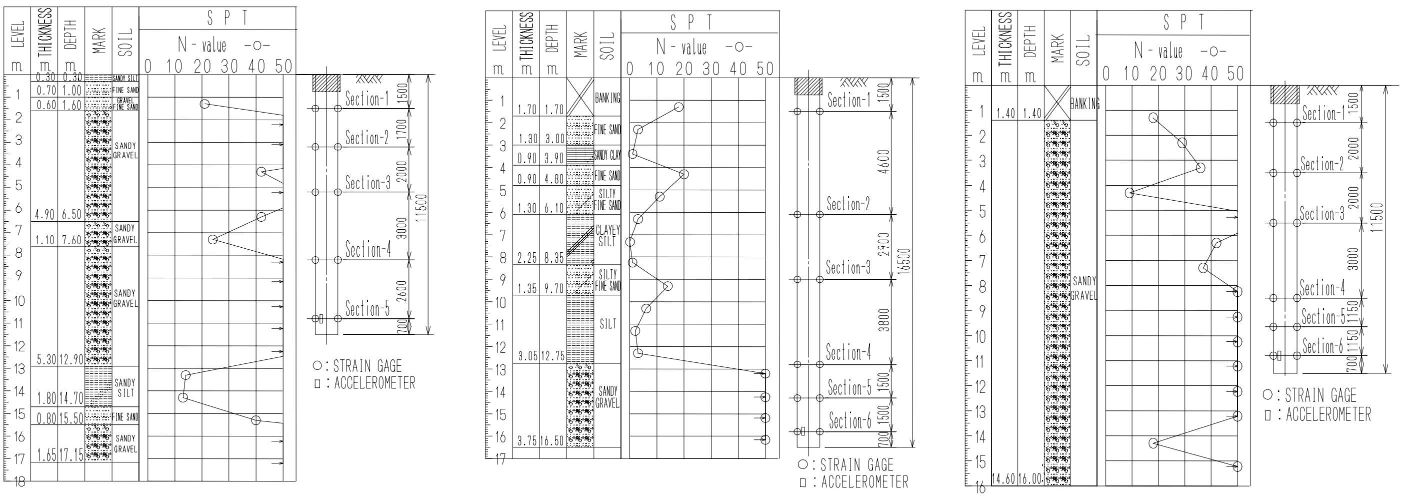
In order to discuss a possibility to shorten the design pile length, the past pile load test results of cast-in-situ piles were reviewed. Those values of the shaft resistance are summarized in Table 1. It is shown that shaft resistance in a sandy gravel layer with N value of larger than 50 would be 300kN/m^2 or more. Then, the pile length can be shortened if it can confirm that the shaft resistance is 300kN/m^2 or more. Then vertical pile load tests were planned for indicate the shaft resistance and total bearing capacity.

3 SOIL PROPERTY AND TEST PILES

The soil boring logs and the test piles specifications of the three sites are shown in Figure 1. The depths of the sandy gravel soil layer where N value is larger than 50 are from GL-8m at Site 1 and Site 3, from GL-13m at Site 2. The designed piles were cast-in-situ piles with diameters of 1.0m by all casing construction method. Since the design pullout loads were large, the piles needed to be installed into the bearing layer with embedded length of over 4.0m. Therefore the lengths of the test piles were determined to be 11.5m at Site 1 and Site 3, 16.5m at Site 2.

Table 1. Reviewed pile load test results of cast-in-situ piles.

No.	Piling method	Pile test	Pile diameter (m)	Final displacement (mm)	N value	Shaft resistance (kN/m^2)	Reference
1	All casing	Compression	1.1	62.5	41	> 340	Aoki (1983)
	All casing	Compression	1.1	36.7	45	> 208	
	All casing	Compression	1.1	36.7	> 50	> 265	
2	All casing	Compression	1.0	13	45	> 170	Aoki et al. (1987)
	All casing	Compression	1.0	13	> 50	> 272	
3	All casing	Tensile	0.8	90.8	50	320	Okuyama et al. (1988)
	All casing	Tensile	0.8	139	50	414	
	All casing	Tensile	0.8	101	50	429	
4	All casing	Compression	1.2	24	40	> 220	Aso et al. (1991)
5	All casing	Compression	1.0	52.7	45	302	Aoki et al. (1992)
	All casing	Pile-toe load	1.0	56.9	45	250	
	All casing	Pile-toe load	1.0	51.1	45	338	
6	All casing	Compression	1.0	> 100	> 50	540	Kito et al. (1996)
	All casing	Compression	1.0	> 100	> 50	540	
	All casing	Tensile	1.0	> 100	> 50	540	
	All casing	Tensile	1.0	> 100	> 50	540	
7	Wall pile	Pile-toe load	0.6/2.52	50	> 50	380	Konishi et al. (1996)
	Wall pile	Pile-toe load	0.6/2.52	40	> 50	> 600	
8	Earth drill	Pile-toe load	2.2	13.1	> 50	> 230	Ogura et al. (1997)
9	All casing	Pile-toe load	2.0	59.9	40	320	Hinohara et al. (1998)
	All casing	Pile-toe load	2.0	59.9	> 50	360	
10	Earth drill	Pile-toe load	1.0	27	50	> 300	Fujioka et al. (1998)
	Earth drill	Pile-toe load	1.2	63	50	340	
	Earth drill	Pile-toe load	1.5	74	50	370	
11	All casing	Rapid load	1.2	49	35	238	Nakayasu et al. (2000)
	All casing	Rapid load	1.2	49	27	208	
	All casing	Rapid load	1.2	49	50	301	



(Site 1. Takaoka) (Site 2. Imizu) (Site 3. Oyabe)

Figure 1. Test Piles and soil properties.

4 HYBRIDNAMIC RAPID PILE LOAD TEST

Hybridnamic test (Miyasaka et al. , 2008) is one of a vertical pile load test methods which excites rapid load by falling a heavy weight to a pile head proposed. Hybridnamic cushion which is an elastomer sheet stuck on a steel plate was innovated for the Hybridnamic test. The Hybridnamic cushions on a pile head can translate impact force by falling a weight to desirable loose rapid force. An equipment of Hybridnamic test and a sheet of Hybridnamic cushion are shown in Figure 2.

Japanese Geotechnical Society standard (2002) asks for relative loading duration T_r to exceed 5 in a rapid pile load test. Relative loading duration T_r is calculated by Equation (1).

$$T_r = \frac{t_L}{2L/c} \tag{1}$$

where,

t_L : loading duration

L : pile length

c : stress wave velocity

In Hybridnamic test plan required weight mass, the maximum falling height, and number of cushion sheet meaning spring constant could be determined by using a single mass and spring model to satisfy planned relative loading duration and planned test load.

Table 2 shows the parameters of the pile load tests conditions including also the falling height orders for the three test piles in this project.

Pile Driving Analyzer (Likins, 1988) was used as a measuring instrument at a pile head, two bridge type strain meters and two accelerometers of a piezo-electric type are attached to the position for an axis. Although time history of displacement is a numerical integration value from the measured acceleration, the integration value is verified with a noncontact displacement transducer.

The test piles were instrumented with steel rod strain gages at four or five level sections along the pile axis. Four strain gages were attached on each level section. Depth of one strain gage section was adjusted so that it might become the same depth as the upper end of the bearing layer, see Figure 1.

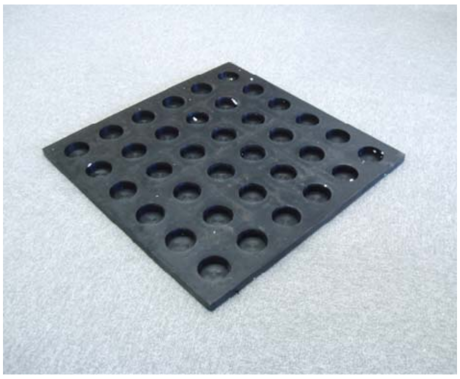
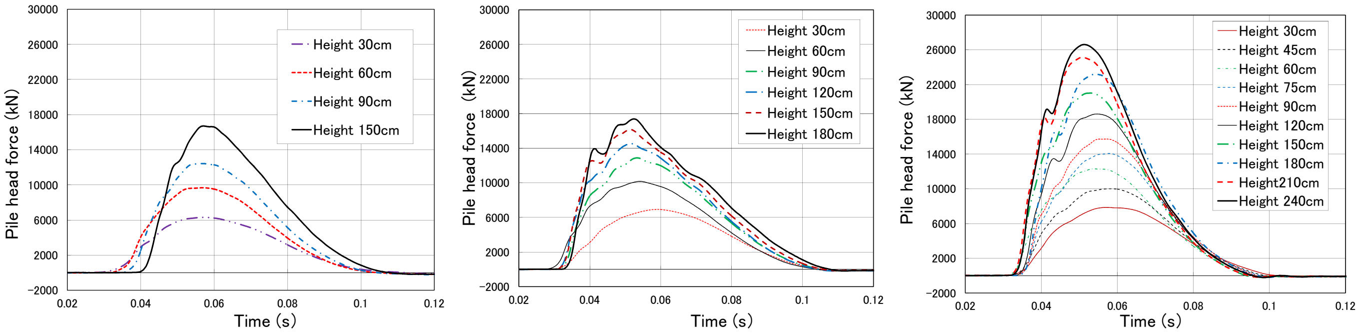


Figure 2. Photograph of Hybidnamic test equipment and a sheet of Hybridnamic cushion.

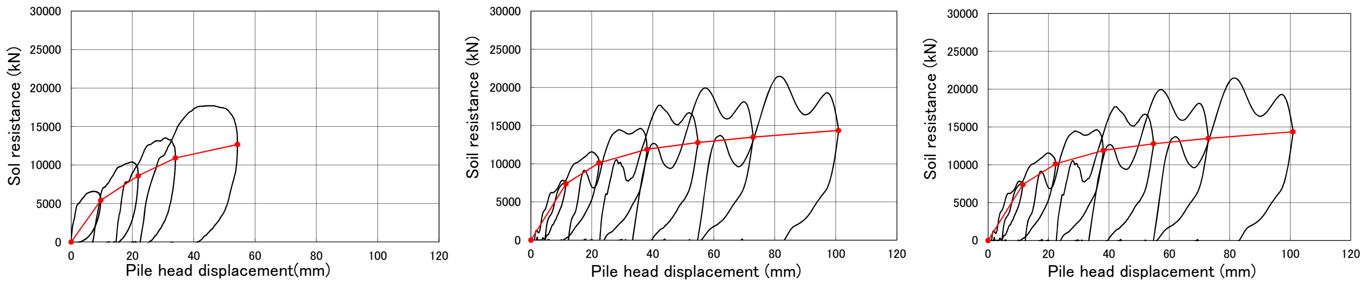
Table 2. Test pile size and parameters of Hybridnamic tests.

Site name	Pile diameter (m)	Pile length (m)	Stress wave velocity (m/s)	Plan relative loading duration	Mass of a weight (ton)	Spring constant of Hybridnamic cushion (kN/m)	Plan maximum test load (kN)	Plan maximum falling height (cm)	Sequence of falling height (cm)
1 Takaoka	1.0	11.5	3500	9	70	1,972	22,800	200	30,60,90,150
2 Imizu	1.0	16.5	3500	6	70	2,170	26,800	250	30,60,90,120 ,150,180
3 Oyabe	1.0	11.5	3500	9	70	1,972	22,800	200	30,45,60,75, 90,120,150, 180,210,240



(Site 1. Takaoka) (Site 2. Imizu) (Site 3. Oyabe)

Figure 3. Rapid load time history.



(Site 1. Takaoka) (Site 2. Imizu) (Site 3. Oyabe)

Figure 4. Static resistance vs. pile head displacement calculated by Unloading point method.

Table 3. Results of Rapid load tests.

Site	Maximum load (kN)	Maximum pile head displacement (mm)	Maximum static resistance (kN)	Static shaft resistance (kN)	Static toe resistance (kN)
1. Takaoka	16,710	54.2	12,670	8,272	4,398
2. Imizu	17,379	100.9	14,359	12,121	2,238
3. Oyabe	26,610	107.9	21,760	13,042	8,718

5 TEST RESULTS

The time histories of rapid load curves of each fall at the pile head measured by Pile Driving Analyzer are shown in Figure 3. The rapid load waveforms are trapezoid. This means that large energy was transmitted to the test piles. The real loading durations of all tests were about 0.065sec. Relative loading duration, calculated with stress wave velocity of 3,500m/sec were 9.9 and it satisfied the planned value of 9.0. The load increasing ratio were about 0.5~1.7MN/ms.

The Hybridnamic test at Site 1 was stopped by the 4th fall by complaint of neighborhood about vibration of the test. At the other two sites, the tests were continuously carried out until the amount of the pile head settlement to be exceeded 10% of the pile diameter.

The soil resistance vs. displacement curves computed by Unloading point method (Kusakabe & Matsumoto, 1995) are shown in Figure 4. It also shows the static resistance vs. displacement curves. The static resistance curves of Site 1 and Site 2 had the almost same behaviors that seemed to be friction piles. The curve of Site 3 had high rigidity relatively. Ultimate failure situations were to be all three curves. The results at the fall of the maximum height in each site are summarized in Table 3. The table also shows the toe and the shaft resistance separated by wave matching analysis (Likins et al. , 1982). Table 3 shows that the maximum loads were from 16.7 to 26.6MN and the maximum static resistances were from 12.7 to 21.7MN. The average value of the rate of the static resistance to the load was 80%.

6 EVALUATION OF SHAFT RESISTANCE

The distributions of shaft resistance were computed by wave matching analysis and sequential unloading point method. The wave matching analysis is based on one dimensional stress wave propagation theory. The sequential unloading point method uses single mass model. In this analysis, first, an analysis for whole length of the pile is carried out with using pile head force, F_0 and displacement, S_0. Secondly, an analysis for a pile element below section 1 is carried out with F_1 and S_1. Thirdly, an analysis for below next section is carried out. Finally an analysis for the pile element below deepest section is carried out with F_N and S_N (See Figure 5). A difference of two continuation analyses is shaft resistance between the two sections. The results of the sequential unloading point method were compared with the results of the wave matching analysis. The differences among both were about 1000kN as shown in Table 4.

Figure 6 shows the distributions of shaft resistance from the results of the wave matching analyses. The figure shows that the shaft resistances of sandy gravel layer with N value of larger than 50 exceeded 300kN/m^2 at all three test sites. Figure 7 shows shaft friction of cast-in-situ piles including data in table 1 and the test results here. The figure indicates that the shaft friction values of this site were appropriate.

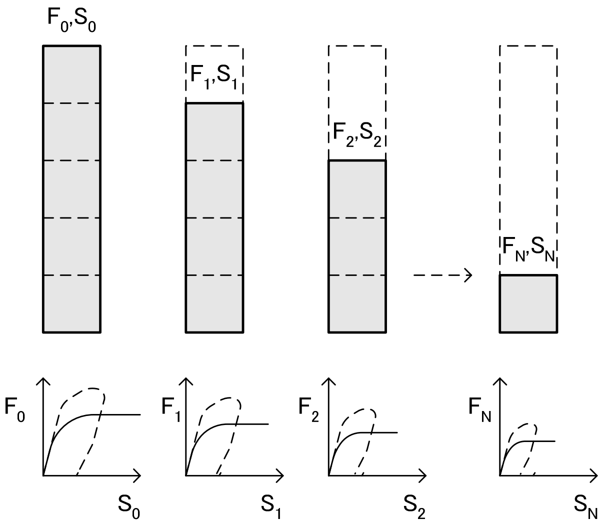


Figure 5. Sequential Unloading point method.

Table 4. Comparison of matching analysis and sequential unloading point method.

Site	Analysis	Static shaft resistance (kN)	Static toe resistance (kN)
1. Takaoka	Matching Analysis	8,272	4,398
	Sequential U. P. M.	9,468	3,202
2. Imizu	Matching Analysis	12,121	2,238
	Sequential U. P. M.	11,753	2,606
3. Oyabe	Matching Analysis	13,042	8,718
	Sequential U. P. M.	11,773	9,987

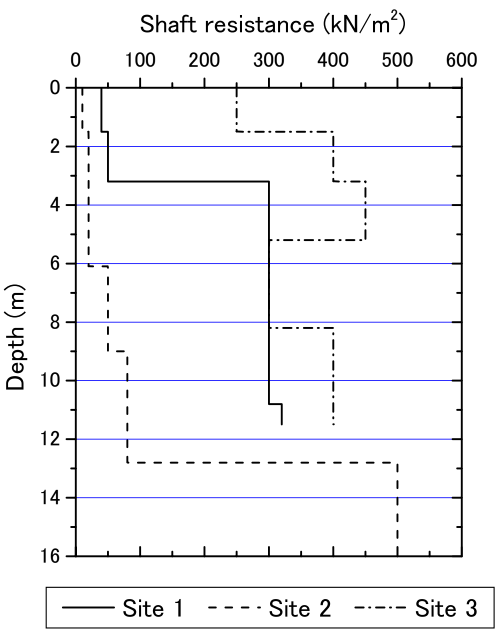


Figure 6. Shaft resistance distributions.

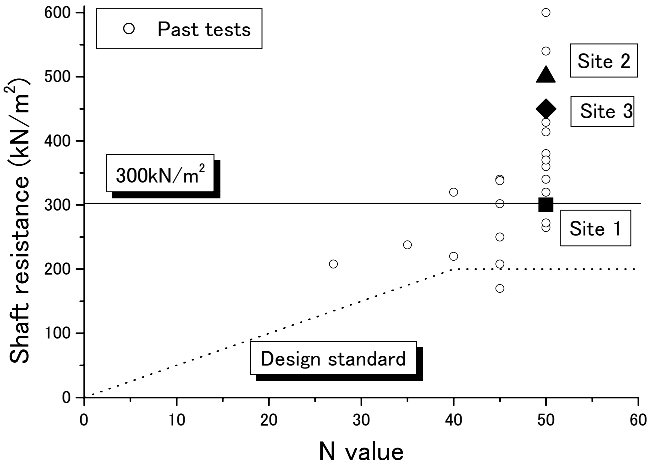


Figure 7. Comparison of Shaft resistance from results of load tests.

7 THE RESULT OF TRIAL CALCULATION TO SHORTEN PILE LENGTH

The bearing capacities of the working pile were calculated based on the results of the rapid pile load tests. Table 5 shows the results of the trial calculations. The Case 1 adopted the values calculated by f=5NkN/m^2 limited up to be 200kN/m^2 according to Japanese design standards for railway structures(2006). In the Case 2 the shaft resistance was calculated by f=5N kN/m^2 limited up to is 300kN/m^2 with limited N value of 60 from the results of the pile load tests. In the calculation results of bearing capacity, the working pile length of Case 2 was able to be shortened a maximum of 3.5m from Case1. However, Case 2 could not satisfy the design limit value of rail displacement. The rail displacement is calculated by using pile head springs compounded from pile body stiffness, vertical and lateral soil springs around piles as shown in figure 8. In consideration of the limit value of the rail displacement, the pile length of Case 3 was able to shorten 3.0m by the maximum from Case 1.

Table 5. Trial calculation for shortening the length of the working pile.

	Case 1 Original	Case 2	Case 3
Upper limited value of friction	200kN/m^2	300kN/m^2	300kN/m^2
The design lateral rate to vertical load as earthquake load when the pile foundation is yield	0.603	0.522	0.571
Rail displacement	82.7mm OK	140.6mm NG	131.9mm OK
Natural period	1.172sec	1.516sec	1.429sec
Total shaft resistance	7657kN	7303kN	7453kN
Pile length	12m	8.5m	9.0m

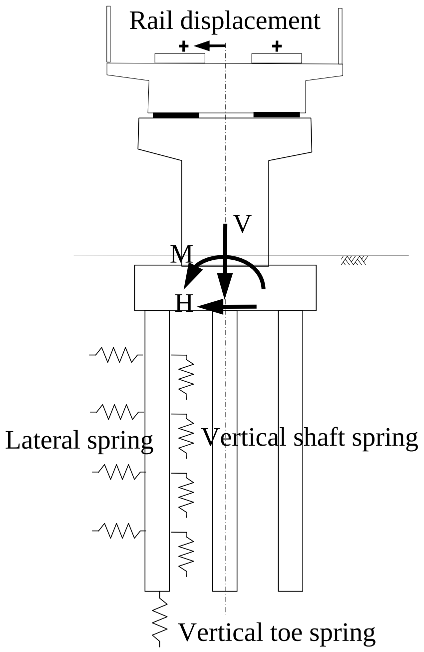


Figure 8. Rail displacement calculation model.

8 CONCLUSIONS

The shaft resistance of the cast-in-situ piles for pier bridges of Hokuriku-Shinkansen super express was indicated by Hybridnamic tests at three sites. The results of the pile load tests could adopt the value of 300kN/m^2. It could shorten the length of the working pile. In the interpretation of the results of the rapid load tests new sequential unloading point method was adopted. The results of the new methods were close to the results of the wave matching analysis.

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