BEARING CAPACITY OF STEEL PILES EMBEDDED IN HARDENING SLURRY

PORTANCE DES PIEUX EN ACIER DANS LA BOUE DURCISSANTE

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SYNOPSIS: Steel I-beam piles, embedded in hardening slurry were widely applied in the Berlinoise support of excavations on the Warsaw Underground construction sites. Because this method of foundation was a new one, investigations were conducted to determine bearing capacity of such piles, as well as the possibility of future recovery of steel beams from hardened slurry. The influence of anti-adhesive coats on the bond characteristics of piles was also tested. The tests indicated, that these coats were not necessary, if the bond between a pile and slurry would be destroyed mechanically prior to extraction..

INTRODUCTION

A few sections of Warsaw Metro were constructed in excavations supported by temporary Berlinoise structure. In the outside of the congested area steel I-beam piles of this structure were driven (Koerner 1984) but such method proved useless in the city, closely to existing buildings because of vibration. Than, a hardening slurry was widely implemented to found piles in the ground. I-beams of 400-500 mm depth were placed into boreholes of.500-700 mm dia (Kłosiński et al. 1987). During the process of boring, the hardening slurry was poured into a hole when the ground water level was achieved. The slurry protected the stability of a hole until it was under boring (Welzien 1985). A typical depth of holes was from 15 to 20 m. Into completed hole filled with the slurry an I-beam pile was placed and fixed at top. After 3-5 days, the slurry hardened and bond a pile with the ground. For embedding of I-beam piles the hardening slurry of designed 28-day compressive strength 0.5-1.0 MPa was used. It was a mixture of water, bentonite, cement and modifying substances. As a modifier, the agent called Rotarmix-1 was mainly applied (Rafalski 1986). It activated particles of bentonite, reduced the viscosity of the slurry and retarded its setting.

This application of the hardening slurry proved very useful. Steel I-beam piles were placed in the ground without noise and vibration, they were well integrated with the ground and the hardening slurry could be dug easily during the process of excavation.

As the bond between a pile and hardened slurry was greater in comparison with a driven pile, the problem of future recovery of piles from the ground was discussed. To reduce the bond, anti-adhesive coats were proposed, but the use of these agents could influence on the load capacity of piles. The problem became important in a case of anchored Berlinoise structure because piles were loaded axially.

To solve these questions, laboratory and field investigations was conducted (Jankowski et al. 1989). The aim of the investigation was:
- to determine the influence of anti-adhesives on the bond between a pile and hardened slurry,
- to optimize the structure of a pile taking into account its load capacity and the future recovery.

LABORATORY TESTS

The laboratory tests concerned the influence of anti-adhesive coats on the bond strength between steel bars and hardened slurry. The concentric pullout test was selected to determine the strength. The testing program consisted of 45 pullout specimens (Fig.1).

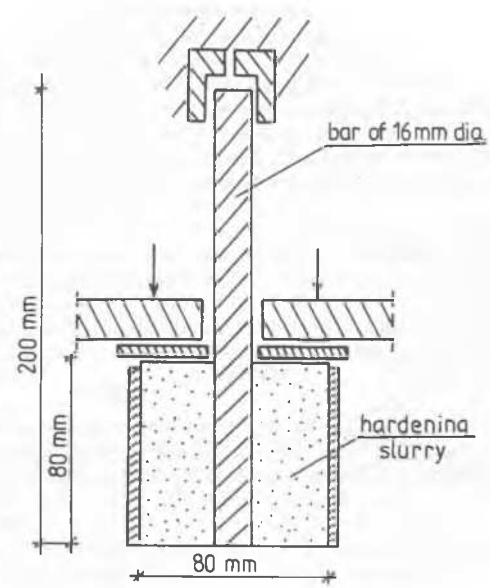

Fig. 1. Pullout specimen with a bar embedded in the hardened slurry

The following anti-adhesives were selected for tests:
* Separbet (an agent used for coating of steel formworks),
* engine oil,

* cup grease,
* oil paint,
* paraffin.

The steel bars had a diameter of 16 mm and a length of 200 mm. They were divided into two groups: rusty and smooth ones, and uncoated or coated by anti-adhesives. Totally, 12 series of 3-5 bars were prepared.

The designed 28 day compressive strength of the slurry was 0,5-1,0 MPa. The slurry was obtained by mixing of water, Rotarmix-1, bentonite "Zebiec" and Portland cement 35. The slurry was poured in forms, then bars were placed vertically and fixed. The embedment length of bars was 80 mm. Additionally, specimens were done to control a compressive strength of the slurry. The pullout and slurry specimens were left at temperature 18 ± 2 degree C and humidity not less than 95 percent. After 28 days pullout tests were performed and the slurry specimens were compressed. All specimens were loaded with a speed of 2 mm/min. The compressive strength of slurry specimen was of 0.61 to 0.72 MPa. The results of pullout tests are given in Table 1.

Table 1. Bar specimen test results

Surface of bars	Anti-adhesive	Bond stress (kPa)
rusty	----------	164
rusty	Separbet	139
rusty	engine oil	155
rusty	cup grease	52
rusty	oil paint	133
rusty	paraffin	74
smooth	----------	152
smooth	Separbet	117
smooth	engine oil	94
smooth	cup grease	49
smooth	oil paint	122
smooth	paraffin	68

The load-slip curves are shown in Fig.2 (smooth bars) and Fig.3 (rusty ones).

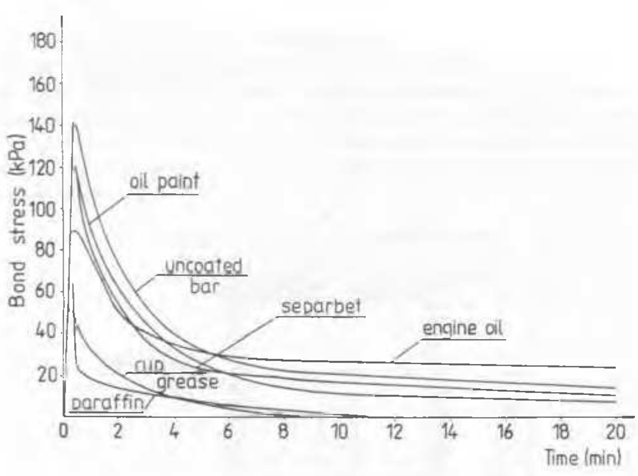

Fig. 2. Bond stress versus time relationship for specimens with smooth bars

The percentage bond of specimens with bars coated by anti-adhesives in comparison with uncoated ones are presented in Table 2.

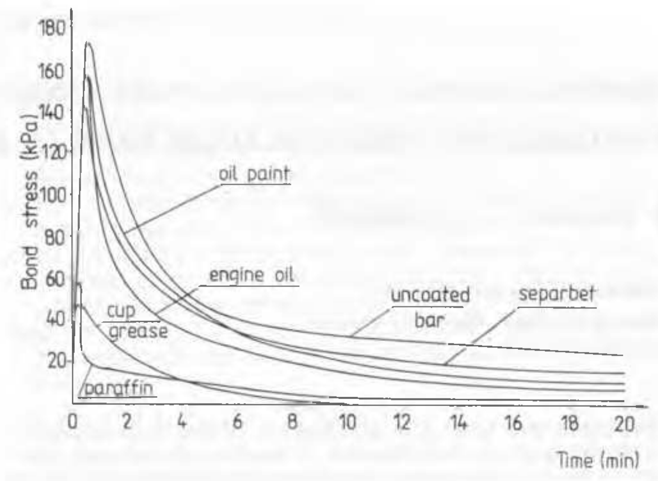

Fig. 3. Bond stress versus time relationship for specimens with rusty bars

Table 2. Percentage bond of specimens with bars coated by anti-adhesives in comparison with uncoated ones

Anti-adhesive	Bar	
	rusty	smooth
Separbet	85	87
engine oil	95	62
cup grease	32	32
oil paint	81	80
paraffin	45	45

The load-slip curves showed a rapid rise to the peak value and then the adhesive bond was broken for both groups of specimens: with smooth and rusty bars. The anti-adhesives coats reduced the bond to 32-95% of uncoated ones. The most considerable reduction was observed for specimens covered by cup grease (32%) and paraffin (45%). Other anti-adhesives reduced the bond to 60-95% relatively to specimens with uncoated bars. The bond values of specimens with rusty bars proved obviously greater than that with smooth bars but differences were considerable for individual anti-adhesives (Table 2).

On the basis of these tests, paraffin was selected for further field investigations.

FIELD TESTS

Test Program

The program included technological trials and statical loading tests on 6 piles of various length and structural details. All piles consisted of an 450 mm I-beam embedded in 650 to 700 mm dia. borehole. Two lengths of the piles were selected:

- 15 m - a typical length of soldier piles used at Warsaw Metro sites,
- piles 8 m deep with 4 m bearing length, representing typical conditions of support after full depth excavation.

The short piles were founded in stiff to hard moraine clays, the long ones penetrated 6 m into a sand layer.

Three kinds of piles were tested:

a) piles fully embedded in a hardened slurry,
b) piles coated with 1 to 2 mm paraffin,
c) pile fully coated as above, with a base of 500x300 mm steel plate 12 mm thick; the base was connected at the end of I-beam by a pin which was cut during the pile extraction.

Two procedures of pile loading tests were planned:

- compressive loadings up to failure, and afterwards statical pulling,
- pullout loading tests.

In total, 6 piles were constructed: two 15 m and four 8 m length. One of the piles had the detachable base. The loading tests included 5 compressive and 6 pullout tests.

Site Conditions

The subsoil conditions at the test location are shown in Fig. 4. Below 1 to 1.2 m fill (with slag, bricks and rubbish), the subsoil consisted of Quarternary layers of overconsolidated glacial clays: stiff sandy clay to 4.1 m depth, very stiff sandy clay to 6.5 m and hard grey clay to 9.5 m. They were underlain by dense medium sands.

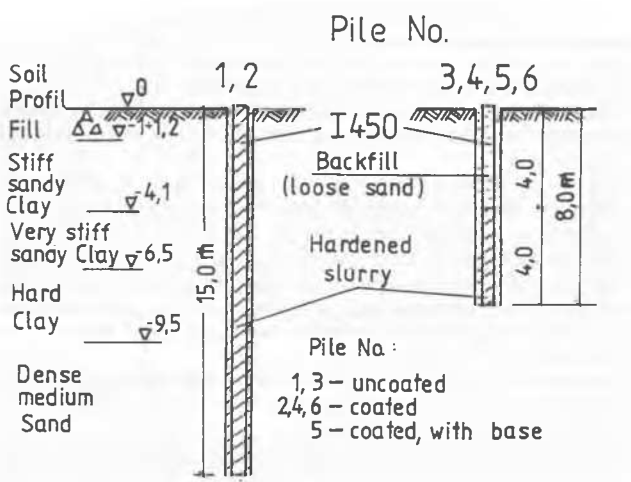

Fig. 4. Subsoil profile and schemes of test piles

Construction of Test Piles

The schemes of test piles are shown in Fig. 4. The hardening slurry of designed compressive strength 0.5 MPa used in the piles had density 1.2 to 1.37 g/cm^3. Samples of the slurry had 28-day strength of 0.47 to 0.70 MPa, average 0.583 MPa. The coating of the four piles was made at the test site. The I-beams were painted with hot paraffin using a brush.

Compressive Loading Tests

An usual procedure of loading was used. The piles were loaded by a hydraulic jack born against a steel reaction frame, which was tied down with ground anchors. Applied loads were checked by a hydraulic dynamometer of 500 kN capacity. Pile movements were measured by dial gauges, read to 0.01 mm, and checked by levelling. The loads were applied in stages and maintained until the resulting movement of a pile substantially ceased.

The load-settlement curves of the piles are shown in Fig. 5.

Piles 15 m long. The uncoated pile No. 1 in the first phase under the load of 500 kN settled only 1.1 mm, and recovered to 0.1 mm after unloading. In the second phase the pile at 1540 kN settled 6.6 mm. During increasing the load to the next stage, the bond of the pile was suddenly sheared at the load of 1680 kN. The pile settled 23 mm while the force fell down to 660 kN. During the subsequent intensive oil pumping to the jack the force reached temporarily only 1050 kN, and it stabilized at 967 kN after the pumping had been stopped.

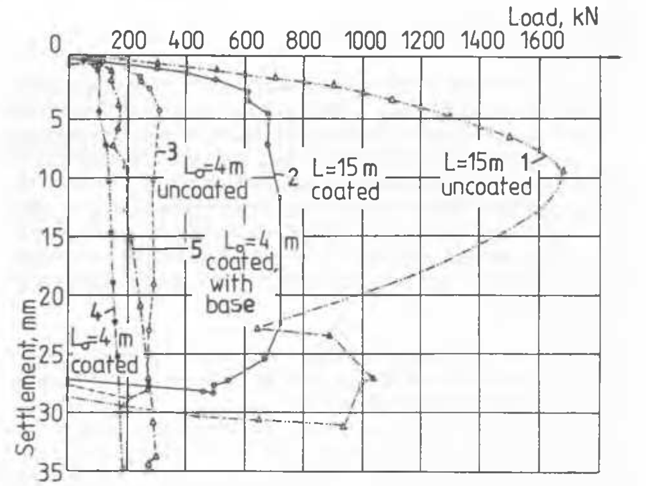

Fig. 5. Load-settlement curves of compressed piles

The coated pile No. 2 at the load of 450 kN settled 1.8 mm and after unloading recovered to 0.6 mm. In the second phase it settled linearly up to 560 kN. The settlement curve bent at 620 kN and under 670 kN the pile continued settling without stabilization. The highest momentary load reached 720 kN at the settlement of 22 mm. The stabilized force was 480 kN. The load-performance of both piles was different. The coating reduced maximal resistance from 1680 to about 700 kN i.e. to 40%. The uncoated pile failed suddenly with a loud noise, while in the case of coated pile a plastic shearing of the paraffin occurred.

Piles 8 m long. The piles had bearing length of about 4 m. The uncoated pile No. 3 settled linearly up to 100 kN, the bond failed suddenly at 308 kN and the pile penetrated with slightly decreasing force. The coated pile No. 4 began to settle continuously under the load of 100 kN. It stabilized at the load of 85 kN and the 5.4 mm settlement. The maximal resistance was about 230 kN.

The second coated pile No. 5, having a detachable base, at the load of 100 kN settled only 0.6 mm. At 150 kN the pile settled 2.5 mm and began to creep. It stabilized at 141 kN. After loading to 180 kN the pile settlement stabilized at the force of 154 kN, and after loading to 200 - at only 122 kN. During intensive oil pumping the force reached 485 kN and the pile stabilized at the force of 414 kN and rather moderate settlement of 52 mm. The use of a base plate increased the ultimate load capacity of the pile over twofold, comparing with the pile No. 4.

Discussion of the results. The main object of the compressive tests was to investigate the load performance of piles embedded in a hardened slurry. The test have shown that:

- the behaviour of a coated and uncoated pile are qualitatively different,
- the detachable base effectively increases the compressive pile bearing capacity.

The both uncoated piles No. 1 and 2 shown small settlements and they quickly stabilized up to the moment of bond failure. Discounting the small resistance of the pile tips, the unit shearing resistance of the piles amounted:

- for pile No. 1 $t = 75$ kPa $= 0.126\ R_{28}$,
- for pile No. 3 $t = 49$ kPa $= 0.104\ R_{28}$,

where R_{28} is an average 28 day compressive strength of hardened slurry samples of the pile. After the bond failure, however, the penetration resistance considerably decreased (to about 70% of the maximal values).

The paraffin coating considerably reduced axial bearing capacities of the piles. For the 15 m pile No. 2 it amounted only 40% of the capacity of the pile No. 1. For the piles No. 3 and 4 the ratio was about 50%. The additional base of the coated pile No. 5 changed its performance. The maximal load as well as the final stabilized force were 1.5 times of these for the pile No. 3.

Pullout Loading Tests

The way of loading was similar as in compression. The main difference was in the exerting of pulling force. A pile head was tied with steel ropes to a beam which acted as a single-arm lever. One end of the beam was supported on a cross-beam laying on the ground surface. The other end was born on a hydraulic jack, by which the beam was pushed up, pulling the tested pile. The loads were applied in stages in 10 to 15 min time intervals up to the moment of "flowing" of a pile under constant load. Considering the purpose of the tests it was not necessary to wait for full stabilization of pile movements. After large uplift of a pile its maximal short-term pullout resistance were determined.

The piles No. 1, 2, 3, 4 and 5 had been 2 to 3 weeks earlier pushed down during compressive test loadings. The pile No. 6 was not previously loaded. The load-uplift curves are shown in Fig. 6.

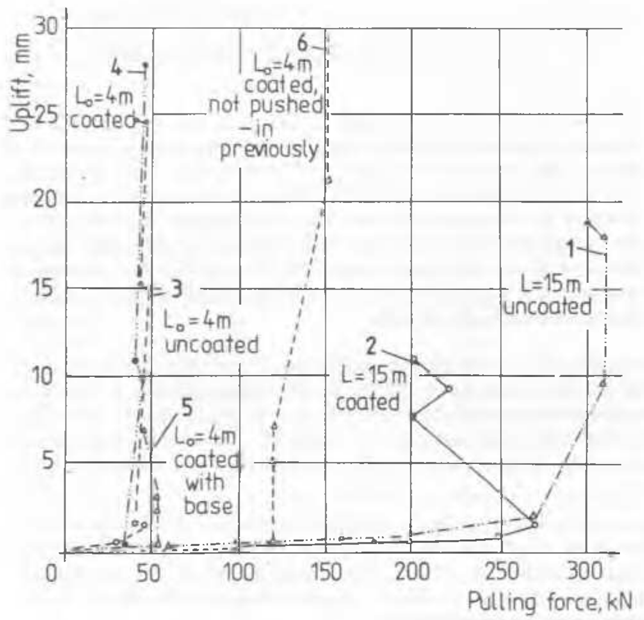

Fig. 6. Load-uplift curves of tension piles

The maximal unit shearing resistances of the piles were the following:

- pile No. 1 (15 m, uncoated) t = 14.1 kPa,
- pile No. 2 (15 m, coated) t = 12.2 kPa,
- pile No. 3 (8 m, uncoated) t = 7.6 kPa,
- pile No. 4 (8 m, coated) t = 6.2 kPa,
- pile No. 5 (8 m, coated, with base) t = 7.4 kPa,
- pile No. 6 (8 m, coated, not loaded earlier) t = 22.8 kPa.

The main object of the pullout tests was to predict probable forces needed for withdrawing of the piles. In particular, the tests should solve the problem: is a paraffin or another anti-adhesive necessary for retrieve of the piles. From the test results some observations has been made:

- due to destroying of the bond between the pile and hardened slurry during compressive tests, the unit resistance of the pullout piles were several times smaller than that in compression test of the same pile;
- unit pulling resistances of uncoated piles after the bond failure were close to that of the coated piles;
- unit pulling resistances of the short piles were in average only about a half of the resistance of the long piles.

The obtained results proved that after shearing of the bond of piles, the pullout resistances were small enough that it would be possible to withdraw the piles without use of any anti-adhesives. The reduction of the resistance on the contact pile-hardened slurry may be attributed to brake down of the structure of cement-bentonite slurry material. The d was caused by pile movements: at first downwards and than upwards. That was confirmed by much higher resistance of the pile No. 6, which had not been loaded in compression. The pullout resistance of the pile No. 5 was slightly increased by the base. However, the base considerably increased the bearing of this pile in compression.

CONCLUSIONS

The use of soldier piles embedded in hardening slurry proved on Warsaw Metro sites to be an effective and cost advantageous method. It enabled safe construction of excavation supports.

The conclusions from the test results were as follows:

1. The hardening slurry ensures stability of pile boreholes even in adverse conditions as well as reliable connection of steel pile with surrounding soil.
2. The shearing performance of the pile-hardened slurry connection was typically brittle. After reaching of a peak value the resistance dramatically decreased to a residual value, as low as about 50% of the peak value.
3. The hardened slurry of the compressive strength $R_{28} = 0.5 \div 1$ MPa gives sufficient axial bearing capacity of piles. Due to brittle character of shearing failure of the material it is possible to pull out a pile by a crane or a pile driving frame after the bond between a pile and hardened slurry is mechanically destroyed.
4. The unit bond resistance between the hardened slurry and the piles was 50 to 75 kPa (equal to 0.1 - 0.125 R_{28}). These values reached only 40 to 50% of the laboratory bond to steel bars.
5. After shearing between the pile and surrounding hardened slurry during push-in and destroying the bond, the residual unit skin resistance of the pullout non-coated piles decreased to 8 - 14 kPa, i.e. to the values close to the skin resistance of the paraffin coated piles (6 - 12 kPa) which had been pushed down earlier.
6. The paraffin coating reduced the pile bearing capacity by 30 to 50%. It also changed the load-settlement performance of a pile.

The obtained tests results and practical experience proved that using of anti-adhesive coatings is not necessary for pile withdrawing in order to be reused.

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