Toe Protection for H-piles on Sloping Bedrock at Rainy River

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Toe Protection for H-piles on Sloping Bedrock at Rainy River

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Summary

Construction of a secondary clarifier on the banks of Rainy River, Northern Minnesota, required the driving of H-piles 14HP102 to a sloping, very strong bedrock through thick deposits of soft and medium stiff soils. Pile toe protection, APF Hardbite HP 77750, was specified to prevent damage to the pile toe and to enable the pile toe to bite into the bedrock surface. The toe protection worked well for bedrock sloping less than 2H:1V. However, where the bedrock was steeper, the piles experienced damage and failed to reach bearing. In most cases, the also the replacement pile failed. Pile Driving Analyzer measurements showed that on encountering the bedrock, the pile toe reflection, which at first was sound, deteriorated indicating pile toe damage. Extraction for visual inspection showed that the failed piles were bent and had deformed pile shoes. In areas of steeply sloping bedrock and for replacement piles, an alternative shoe, the Scanpile Herkules rock shoe, was employed. This pile shoe proved to be able to secure the pile toe into the rock and to eliminate the problem. The costs of the Herkules rock shoe considering price, shipping, and attaching, were about equal with the Hardbite shoe.

Introduction

Construction of a clarifier on the banks of Rainy River, International Falls, Minnesota proved to be a challenge to both the piling contractor and the engineers. H-piles were driven to glacier polished, sloping bedrock through deposits of soft and medium stiff soils. Despite toe protection, many of the piles failed to cut into the bedrock, but rather deformed structurally at the toe and deflected without achieving adequate toe bearing.

The site is located on the south bank of the Rainy River in International Falls, Minnesota on the border between USA and Canada. Construction of the 220 feet (67 m) wide, circular clarifier on compressible soil required a deep foundation system that extended to bedrock and 14HP102 H-piles were selected. Fig. 1 shows the layout of the piles and the contour lines of the bedrock surface.

The original ground surface at the site slopes from a bench away from the river of approximately Elev. 1,120 feet to Elev. 1,070 feet (340 m to 326 m) at the river. Mean river elevation is 1,076 feet (328 m). The geotechnical investigation revealed miscellaneous fill extending from ground surface to depths of 20 to 50 feet (6 m to 15 m) made up of sand, silty sand, clay, lime sludge waste, shredded wood, pockets of boulders, and rubble. The natural soils below the fill at approximately Elev. 1,060 feet (323 m) consist of a high-plasticity lacustrine clay that is underlain at some locations by a thin layer of sand and gravely sand. Over parts of the site, the layer of sand and gravely sand is absent. The overburden soils are underlain by a gneiss bedrock, sloping an average 2H:1V toward the river. The depth to the bedrock from the ground surface ranges from approximately 40 feet through 100 feet (12 m through 30 m). The bedrock surface is polished by glacier action. Although no strength tests were performed on the bedrock for this project, the strength characteristics are known from a previously constructed adjacent clarifier, where the strength of the rock was derived from unconfined compression tests and found to vary from a low boundary of 15,000 psi (100 MPa) to values greater than 35,000 psi (240 MPa), classifying the rock as very strong.

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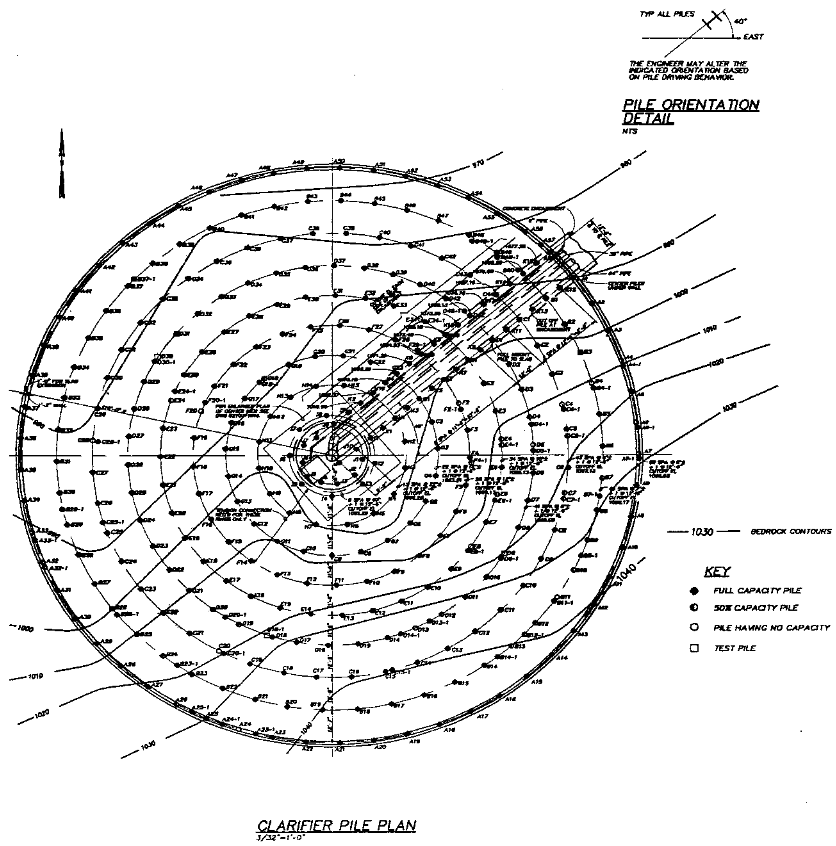

Fig. 1 Layout of piles and bedrock contour lines

Pile Foundation Design

The foundation design was significantly influenced by schedule considerations and by the owner's previous experience with the H-piles for other plant facilities. Further, the deadline for having the clarifier in service required that the piles be ordered prior to the completion of the geotechnical exploration programme.

The final design included approximately 400 piles distributed evenly over the footprint of the clarifier at a spacing of approximately 12 feet (3.6 m). The piles were to be driven to bedrock to support a service load of 70 tons/pile (620 KN/pile), corresponding to an allowable stress of 4.7 ksi (32 MPa). A review of manufacturer's literature indicated that the APF Hardbite HP77750 shown in Fig. 2 had the steepest point and it was specified for use on the project. This shoe is made from hardened steel and designed to bite into the bedrock or catch onto any irregular surface feature to hold the pile toe in position.

It was known from the construction of the adjacent clarifier that difficulties would likely occur when trying to seat the piles into the bedrock**:** Approximately 12 percent of the piles of the same type and size (14HP102) were reported to have failed at the adjacent clarifier despite being equipped with a protective shoe. The owner therefore elected to order extra pile lengths to cover replacement of approximately 12 percent of the piles.

Pile Testing

Ten indicator piles were driven prior to the production pile driving using a Vulcan 512 single-acting air hammer, which has a ram weight of 12 kips (5,400 kg) and a ram stroke of 5 feet (1.5 m). The hammer was equipped with an adjustable slide wedge so that the ram stroke could be reduced by as much as one-half. The test driving included monitoring with the Pile Driving Analyzer (PDA). The primary purpose of the test driving was to establish a penetration resistance termination criterion that would ensure the bearing capacity while minimizing the risk for damage to the pile.

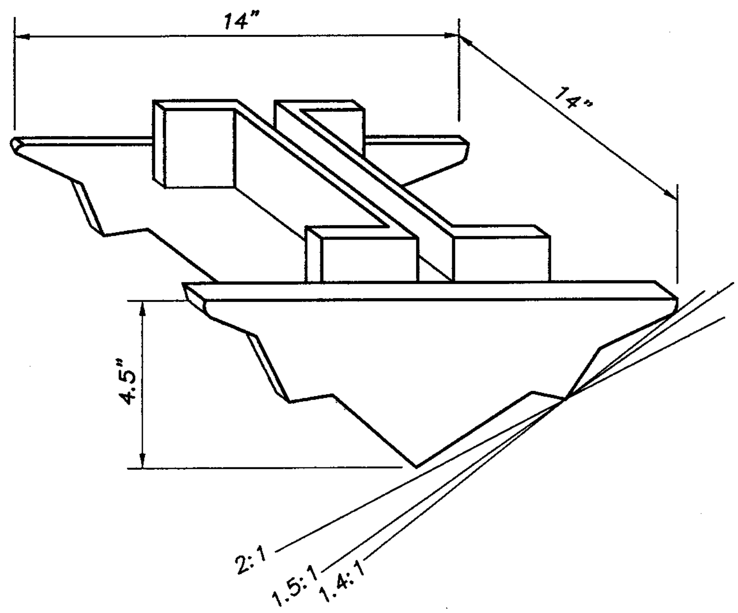

Fig. 2 Geometry of the Hardbite HP77750 rock shoe
(14 inch = 356 mm, 4.5 inch = 114 mm)

Driving of the indicator piles through the overburden was easy**:** The penetration resistance (blow count) was about 10 to 20 blows/foot (30 to 70 blows/m) or smaller. In contrast, when the pile toe encountered bedrock, which occurred suddenly, the resistance increased to values of 10 blows/inch (10 blows/25 mm) and greater. The PDA measurements show that, on encountering bedrock, transferred energy was about 27 ft-kips (37 KJ), impact force was about 650 kips (1,300 KN) and impact stress was about 22 ksi (150 MPa).

Seven of the indicator piles drove to proper seating on the bedrock. However, for the other three piles, the pile toe did not seat properly and the piles were damaged during continued driving. The behavior of these piles during the driving through the overburden was similar to that of the others and, on reaching bedrock, as for the others, the penetration per blow decreased for the first few blows. Thereafter, however, the penetration per blow increased**;** the blow-count reduced to about 2 blows/inch (2 blows/25 mm). Neither of the three piles reached adequate penetration resistance during the continued driving. Even when protracting the driving for several feet, the resistance did not again go beyond about 2 blows/inch.

Insight to the pile behavior is contained in the PDA records as illustrated in Fig. 3. Fig. 3a presents the wave traces obtained shortly before the pile toe encountered the bedrock, as obtained from one of the three failed indicator piles. The figure includes the Force and Velocity trace pair and the Wave-Up and Wave-Down trace pair. The records obtained for this blow are practically identical to the traces obtained from preceding blows and indicate a small shaft resistance, as evidenced by the small separation of the force and velocity traces. At

Time 2L/c, the velocity increases and force goes to zero, which indicates almost total absence of toe resistance further emphasized by the Wave-Up trace. The penetration resistance is about 20 blows/foot (65 blows/m).

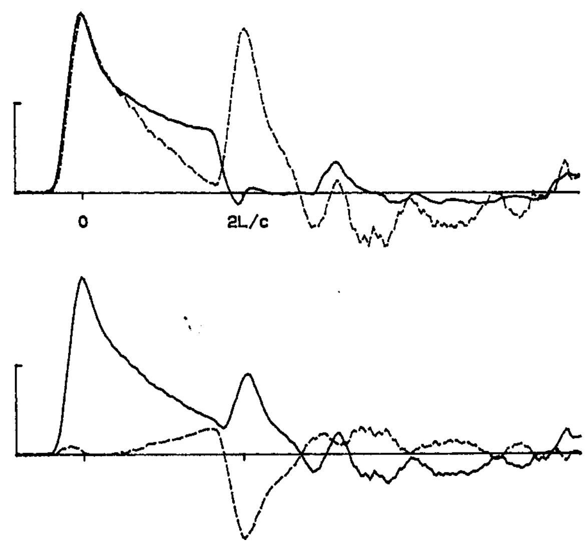

Fig. 3a PDA traces immediately before the pile reached bedrock

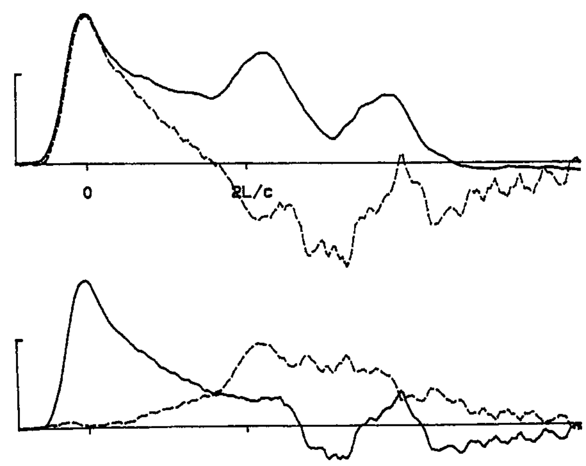

Fig. 3b PDA traces eight blows after the pile reached bedrock

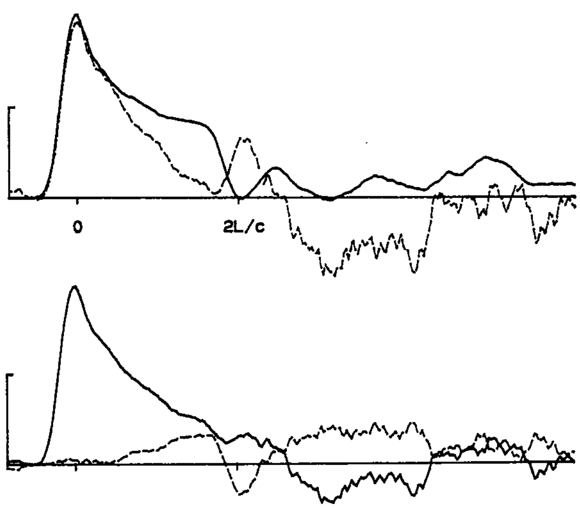

Fig. 3b PDA traces forty blows after the pile reached bedrock

FIG. 3 LEGEND

Upper trace pairs: Force and Velocity

Lower trace pairs: Wave-Up and Wave-Down

During the next blow, the pile toe made contact with the bedrock and a positive toe reflection built up for the following blows. Fig. 3b shows the traces obtained eight blows later. The trace is associated with a penetration resistance of about 7 blows/inch (7 blows/25 mm). Before the toe reflection appears in the record, the traces are very similar to those of the first blow. However, at 2L/c, there is a distinct toe reflection evident in both the force and velocity traces as well as in the Wave-Up trace.

Fig 3b is representative for approximately the next twenty blows. However, thereafter, the appearance of the traces alternated between that shown in Fig. 3b and that of Fig. 3c, obtained 50 blows after the blow record shown in Fig. 3a. The latter traces lack the distinct toe reflection and the records contain more "noise". The pile had "penetrated" approximately 6 inches (150 mm) for the blows and the penetration resistance had reduced to 5 blows/inch (5 blows/25 mm). In continued driving, the penetration resistance reduced further to about 2 blows/inch.

The wave traces were interpreted as follows**:** in places where the pile toe met with steeply sloping bedrock, the Hardbite pile shoe could not secure a hold on the bedrock. Therefore, the pile toe started to slide. On continued driving, the lower end of the pile started to bend and a dog leg developed causing the pile to deform and the sliding to get worse. Indeed, once sliding starts, although there is resistance and some blows indicate capacity, the capacity is uncertain and can not be relied on. Continued driving only results in further bending and damage to the pile.

The measurements showed that, consistently, adequate capacity was obtained more or less immediately on encountering the bedrock surface at an equivalent penetration resistance of 10 blows/inch (10 blows/25 mm). However, driving "the full 10 blows" once bedrock was encountered proved to increase the occurrence of pile damage. The termination criterion was established that on encountering bedrock, which was obvious from the change of driving behavior, five more blows were to be given to the pile and if the penetration for the sum of the five blows was smaller than 0.5 inch, the pile driving was terminated. If the penetration resistance exceeded 0.5 inch for five blows, an additional five blows were to be given, taking care no to drive any more blows than necessary.

The service loads are small and further testing proved that adequate capacity could be achieved by driving with the stroke reduced to one-half. Therefore, the contractor elected to mobilize a smaller hammer**,** a single acting Vulcan 506 air hammer, which has a ram weight of 6.5 kips (3,000 kg) and a ram travel of 5 feet (1.5 m). The same termination criterion was applied.

Production Pile Driving

When the first 50 to 75 production piles had been driven, about 25 percent of the piles had failed in a manner similar to the three failed indicator piles. In most cases, driving the replacement pile also proved unsuccessful. The failures occurred in areas where the bedrock contour lines (Fig. 1) indicated that the slope exceeded 2H**:**1V. The piles performed well in areas where the bedrock surface sloped less. On very steep areas, the rate of success was extremely poor.

Three of the production piles suspected of damage were extracted for visual inspection. All three piles were found to be bent and have deformed pile toes. Fig. 4a shows a photo of the toe of one of these piles after extraction. The photo shows that the flanges have folded over at the side of the pile shoe. This had the effect that the shoe became a "sleigh" with "runners" causing the pile toe to slide on the bedrock. The continued driving caused the pile to bend (the pile can be seen curving behind the pile toe in the photo). The photo shown in Fig. 4b (from a different pile) further illustrates the doglegged shape of the pile caused by the sliding of the pile toe on the bedrock. The primary cause of failure appeared to be the inability of the shoe to sustain the high eccentric point loading and associated high stress near the corner of the flanges.

The inability of the pile to grip and penetrate the bedrock surface is not considered due to any defect in the Hardbite shoe, but a consequence of the steep and strong bedrock surface. Where conditions were less extreme, piles with the Hardbite shoe met the required termination criterion and showed no sign of sliding or toe damage.

Fig. 4a Damaged pile and Hardbite pile shoe after extraction

Fig. 4b Doglegged pile during extraction

Alternative Pile Toe Protection

The high failure rate associated with the difficulties in achieving adequate bedrock support, coupled with the limited supply of replacement piles, prompted a review of other pile shoes available on the market, including those provided by foreign manufacturers. The review showed that the Herkules rock shoe from Scanpile, Sweden, has a long-term proven record of enabling a pile to sustain high stress concentrations and to cut into very strong rock, as well as minimizing bending stresses due to eccentric loading. The Herkules shoe also proved to be cost competitive with shoes from US manufacturers.

The geometry of the Herkules shoe is illustrated in Fig. 5. Its main component is a small-diameter dowel of specially hardened steel alloy inserted in a laterally supporting cylinder and bearing on a steel plate. The concave shape of the dowel end and the very pointed appearance of the shoe ensures that the dowel contacts the bedrock surface before the side of the shoe or pile, thereby keeping the toe force concentric with the pile.

It is important that the hardening is done so that the dowel steel does not become too brittle and shatter on impacting the bedrock. Furthermore, the steel in the main body of the dowel must be strong enough to serve as a reliable base for the hardened 'skin' of the concave dowel end. To maintain the hardness of the dowel, the dowel is not welded to its support (which would destroy the hardening) but held in place by a set-bolt through the wall of the supporting steel cylinder. (The Herkules rock shoe is not the same as what is commonly known a the Olso-point. The latter is a generic term for a shoe with a larger diameter dowel of mild steel welded to a base plate or cylinder and with no or little hardening of the dowel end).

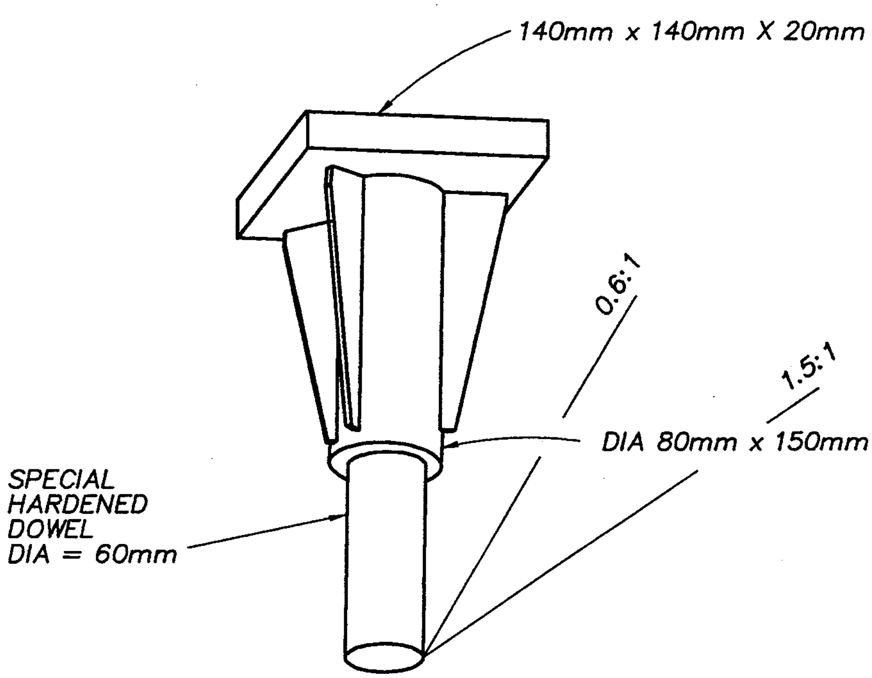

Fig. 5 Geometry of the main component of the Scanpile Herkules rock shoe
(140 mm = 5.5 inch, 20 mm = 3/4 inch, 60 mm = 2.4 inch)

A supply of Herkules shoes was ordered from the manufacturer's stock and air-shipped to the site to be used as an alternative to the Hardbite shoe in areas where the bedrock was steep. Figs. 6a and 6b show photos of piles lying on the ground with the Herkules shoe attached ready to be picked-up and driven. Some of the piles with the Herkules shoe were driven as replacement piles directly adjacent to failed piles (within 2 feet-0.6 m). In every case, the piles with the Herkules shoe drove well and to the specified termination criterion.

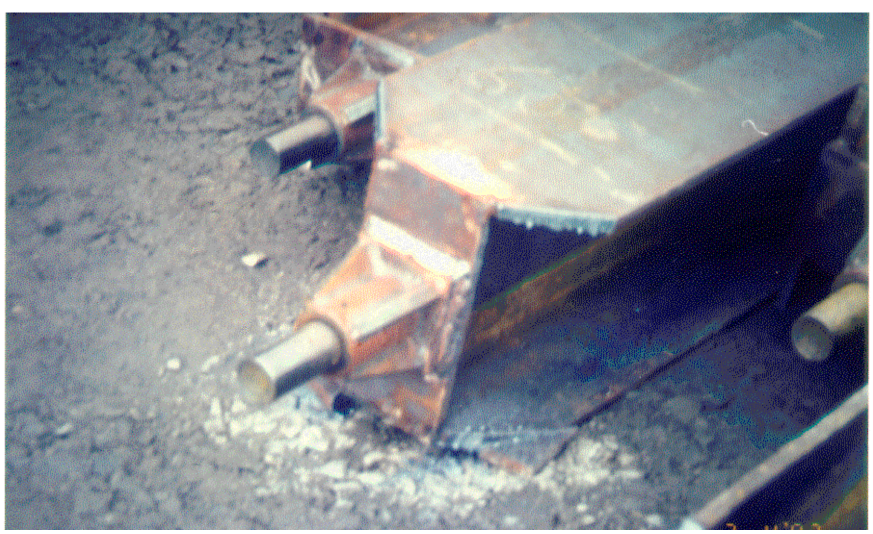

Fig. 6a H-pile with the Herkules rock shoe attached

Fig. 6b H-piles with the Herkules rock shoe attached ready to be driven

Conclusions

The pile toe protection system selected during the design (APF Hardbite HP 77750) performed well in areas where the slope of the bedrock surface was smaller than 2H:1V. In areas where the bedrock sloped steeper, pile damage generally occurred as the pile encountered the bedrock. The damage appeared to be the result of high eccentric point loading at the corner of the shoe (pile flange) as the pile impacted the bedrock, causing the corner of the flange to fold back and allowing the pile toe to slide on the bedrock surface.

The problem was remedied by using an alternative pile shoe (the Herkules rock shoe manufactured by Scanpile, Sweden). The design of the Herkules rock shoe is well suited for piles driven onto steeply sloping bedrock. The hardened dowel allows for high compressive stress and is well supported to distribute the load uniformly at the base of the pile. The concave shape of the dowel and the overall pointed shape of the shoe allow the dowel to encounter the rock surface before the sides of the shoe or the pile, thereby ensuring that the force at the base is concentric with the long axis of the pile. The wave traces provided by the dynamic measurements demonstrated the toe response and proved a valuable asset in understanding the pile performance and conditions a the pile toe. The correlation between the penetration resistance in the bedrock and the condition of the pile toe, as made clear by the PDA wave traces, was indispensable in determining when to accept or to replace piles.

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