KAWASAKI STEEL TECHNICAL REPORT

No.21 (November 1989)

Civil and Architectural Engineering

Development of Underwater Plasma Arc Cutting Method for Interlocked Steel Pipe Piles

Tsutomu Fujita, Hidetoshi Imura, Kohzo Akahide, Tateshi Koseki, Masaharu Hashimoto

Synopsis :

Interlocked steel pipe piles are driven into the ground for construction of piers located in rivers or the sea. In such cases underwater cutting is often required at the end of construction. Cutting of junction pipes is so hard that the pipes will usually be cut before driving. This construction method sometimes causes troubles of water leakage and so on during construction. An effective underwater cutting machine system has been developed to solve these problems. It can cut not only pipe piles but also junction pipes. The system is mainly composed of a plasma arc cutting device and a grindstone device. The mechanism is simple and remote-controlled using some sensors attached. Work time needed for cutting a 800-mmφ steel pipe pile and a couple of junction pipes is about 20 minutes, and thus an efficient automatic underwater cutting method has been established.

The body can be viewed from the next page.

Development of Underwater Plasma Arc Cutting Method for Interlocked Steel Pipe Piles*

Tsutomu Fujita
Senior Researcher,
Construction
Method Lab., R & D
Center, Engineering
& Construction Div.

Hidetoshi Imura
Senior Researcher,
Construction
Method Lab., R & D
Center, Engineering
& Construction Div.

Kohzo Akahide
General Manager,
R & D Center,
Engineering &
Construction Div.

Tateshi Koseki
Staff Manager,
Construction Materials
& Engineering Services
Dept., Engineering
& Construction Div.

Masaharu Hashimoto
Staff Manager,
Construction Materials
& Engineering Services
Dept., Engineering
& Construction Div.

Synopsis:

Interlocked steel pipe piles are driven into the ground for construction of piers located in rivers or the sea. In such cases underwater cutting is often required at the end of construction. Cutting of junction pipes is so hard that the pipes will usually be cut before driving. This construction method sometimes causes troubles of water leakage and so on during construction. An effective underwater cutting machine system has been developed to solve these problems. It can cut not only pipe piles but also junction pipes. The system is mainly composed of a plasma arc cutting device and a grindstone device. The mechanism is simple and remote-controlled using some sensors attached.

Work time needed for cutting a 800-mmϕ steel pipe pile and a couple of junction pipes is about 20 minutes, and thus an efficient automatic underwater cutting method has been established.

1 Introduction

In recent years, many bridges have been constructed over rivers, near seacoasts, and in harbors in Japan, where it is difficult to obtain more suitable sites for roads and railroads. Most bridges are long and it is necessary to install underwater foundations. The foundation method commonly employed uses interlocked steel pipe piles both for foundation support and for temporary cofferdams to permit excavation in dry and ensures easy execution of construction in bad soils. When this method is employed, it is necessary to remove the excess upper portion of the steel pipe pile wall used for the cofferdam by cutting it under water or in the earth near the seabed or river bottom.

In addition to grinder cutters[1) and disc cutters[2), cutting methods with oxygen arcs[3), etc., have been developed and put into practical use to cut the main pipe walls of interlocked steel pipe piles. Mortar-filled steel pipes are generally used as junction pipes to connect the main pipes. It is not easy to cut the junction pipes under water by remote control. For this reason, the precut method has been widely used so far. In this method, part of the junction pipes are gas cut before the steel pipe piles are driven and the opening made by this precutting is filled with a watertight sealant. An example of this method is shown in **Fig. 1**. Using this method, problems such as need of cutting junction pipes occur in case of shallower or deeper than predetermined positioning of precut steel pipe piling when they are driven during construction, or water leakage sometimes occurs. If the junction pipes can be cut efficiently, it is possible to adopt the non-precut method, eliminating the need for advance gas cutting of the junction pipes and thus solving these problems. Although simultaneous cutting of the main pipes and junction pipes had been studied, a good method had not yet been developed, partly because of problems with the

* Originally published in *Kawasaki Steel Giho*, **20**(1988)4, pp. 279–284

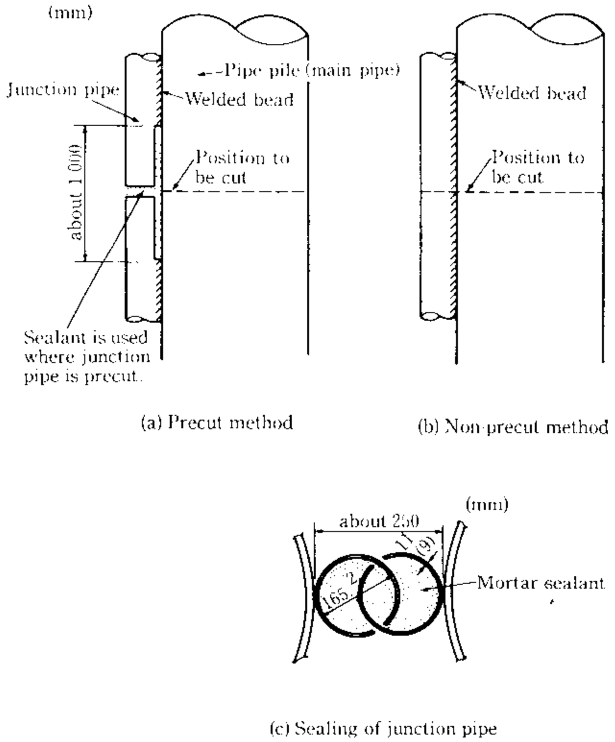

Fig. 1 Precut and non-precut configurations of junction pipes

cutting itself.

With this background, various experiments were conducted in methods of simultaneously cutting the main pipes and junction pipes of interlocked steel pipe piles in order to establish a non-precut method. As a result, a new technique in which the junction pipes are cut with a grinder cutter and the main pipes are cut using the plasma arcs was established. This report presents an outline of this underwater cutting method for interlocked steel pipe piles and describes the plasma cutter developed.

2 Basic Conditions for Underwater Cutting Method for Non-Precut Steel Pipe Piles

Table 1 summarizes the cutting methods which have been put into practical use or may be used with respect to interlocked steel pipe piles used both as foundation support and as temporary cofferdams for dewatering foundations. All these methods have advantages and disadvantages. The disc cutter (metal blade) method where the cutter is set inside of the main pipe has been adopted frequently for cutting the main pipes because it offers high cutting speed and ease of operation. For the mortar in the junction pipes, however, a metal blade is not efficient, while electric arc cutting is in principle difficult because of the lack of conductivity.

Based on various experiments and experience, the grinder method is judged most suitable for cutting the junction, which is a composite of steel and mortar. This cutting method generally has the disadvantage that the grindstone disc may break or can be caught and lodged in the work. A condition for avoiding this problem is that the junction pipes be cut before deformation and displacement occur in the main pipe and junction pipes. When the cutting sequence is main pipe–junction pipes, deformation and displacement occur in the main pipe because the restraint of the main pipe weakens in the final stage of cutting of the junction pipes, rendering this method impractical. Although the above-mentioned condition for successful cutting cannot be satisfied if the main pipe is cut first, if the cutting order is reversed and the junction pipes are cut first, this condition can be met. Deformation and displacement are then concentrated in the main pipe because in this cutting sequence, the junction pipes are cut before the completion of cutting of the main pipe. It is desirable therefore that a noncontact cutting method, which avoids the effects of the pipe deformation and displacement, be adopted in cutting the main pipes.

Noncontact cutting methods include the plasma arc method, water jet method, and oxygen arc method. The

Table 1 Underwater cutting methods

Type of energy	Method	Cutting Method
Mechanical	Grinding	Grinding by grindstone
	Cutting	Cutting by metal blade
	Jetting	Abrasive water jet
Electrical	Plasma	Plasma arc Plasma jet
	Electric discharge	Oxygen-arc Smelting electrode with water jet Arc-saw
Optical	Laser	
Chemical	Blast	Blast cutting (Neumann effect)

plasma arc method is the best method for cutting the main pipes based on an overall evaluation, taking into consideration the environmental conditions when steel pipe piles are installed in rivers and large bodies of open water.

The basic design concept for the underwater cutting method and apparatus used for non-precut pipes was determined as follows:

(1) Final cutting is made in a noncontact manner.
(2) The cutting sequence is junction pipes—main pipe.
(3) The junction pipes are cut with a grinder and the main pipe with a plasma arc.
(4) A single apparatus is used to perform both cutting operations described in (3).
(5) The cutting level of the main pipe is the same as the junction pipes.
(6) The cutting operation is controlled from the ground or on board by remote control.

3 Fundamental Examination of Cutting Method

In order to establish a method for cutting the main pipes and junction pipes with a single apparatus, experiments were conducted in cutting the junction pipes with a grinder cutter and the main pipes using plasma arc.

3.1 Cutting Experiment Using Grinder Cutter

3.1.1 Method of experiment

A cutting experiment using a grinder was conducted in a water tank. The test junction pipe was a steel pipe of 165.2 mm outside diameter and with a 9 mm wall thickness. The pipe was filled with mortar with a compressive strength of 240 kgf/cm^2. The main test pipe was obtained by cutting off part of a steel pipe of 800-mm outside diameter with a 16 mm wall thickness. The junction pipe was welded to the main pipe.

The power required for rotation during the cutting with the grinder cutter and the cutting force were determined from measured values of power.

3.1.2 Rotations and rotation resistance of grinder cutter

The friction loss L_f (kW) when the grinder cutter rotates under water is theoretically determined from the following equation:

$$L_f = k\rho U^3 D^2$$

where ρ: Density of fluid (kg/m^3)
U: Circumferential speed of disc (m/s)
D: Diameter of disc (m)
k: Friction coefficient of disc

Results of this experiment are shown in **Fig. 2**, where $k = 2.9 \times 10^{-6}$. It is apparent that the friction loss of the grinder cutter under water increases exponentially with increasing speed of rotation. Although an appropriate circumferential velocity range of a grinder cutter in air is generally 2 000–3 500 m/min, it is concluded that cutting should be conducted at low or medium speeds of less than about 1 600 m/min under water due to the large friction loss otherwise incurred.

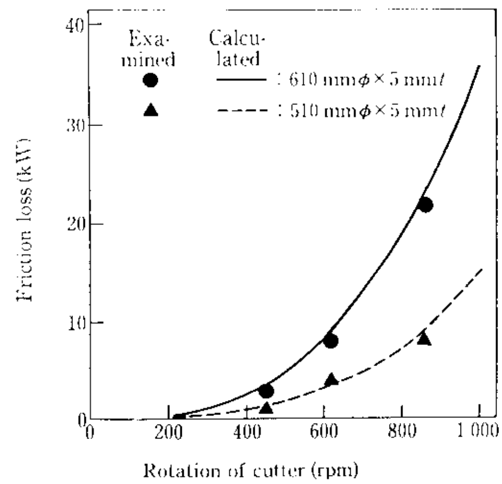

Fig. 2 Relation between rotation of cutter and friction loss

3.1.3 Cutting force and required cutting time of grinder cutter

Figure 3 shows the relationship between the cutting force acting on the grinder cutter per unit thickness ($A = F_t/t$) and the required cutting time when the circumferential speed of the grinder cutter is 1 000 m/min. The required cutting time for the junction pipe decreases but the amount of abrasion increases with

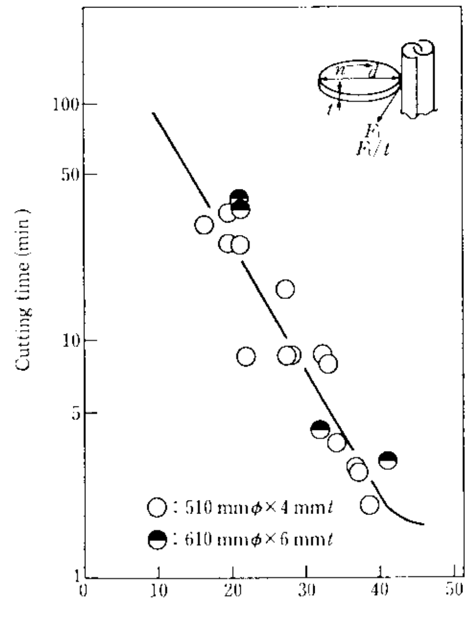

Fig. 3 Relation between cutting force and cutting time

increasing cutting force, indicating that there is an appropriate cutting force range. When the cutting force was about 25 kgf/mm, the amount of diametral wear was about 20 mm. It was possible to cut one or more steel pipe piles with one grindstone, and the time required for cutting the junction pipe was about 10 min. This was considered an acceptable cutting condition.

3.2 Cutting Experiment using Plasma Arc

3.2.1 Experiment method

A plasma arc cutting device HT-400S made by HYPERTHERM was used in this experiment. The original device was modified to allow cutting at water depths down to 30 m by extending the cable from the power supply proper through an intermediate station.

A hydraulic tank that permits cutting simulation experiments at water depths of 30 m maximum is shown **in Fig. 4**. A traveling car to place test samples is installed in the tank; the speed of this car can be controlled by a drive system outside the tank. One of the sides of the tank is provided with a mount on which the torch is set. The distance (standoff) between the torch and the surface of the test steel plate was adjusted to 8 mm and the drag angle of the torch was set at 15°. The tank was filled with tap water or sea water so that the water depth of the torch was fixed at 100 mm. The upper part of the tank was provided with a nitrogen supply port, and the inner pressure of the tank was adjusted with nitrogen. When oxygen was used as the plasma gas, the cutting current was 260 A, the nozzle port diameter was 2.5 mm, the supply gas pressure was 8.5 kgf/cm^{2}G, and the gas flow rate was 50 l/min. For nitrogen, the cutting current was 400 A, the nozzle port diameter was 4.2 mm, the supply gas pressure was 9.9 kgf/cm^{2}G, and the gas flow rate was 80 l/min. Test steel plates used were wedge shaped with one end 5 mm while the other end 27 mm in thickness, and

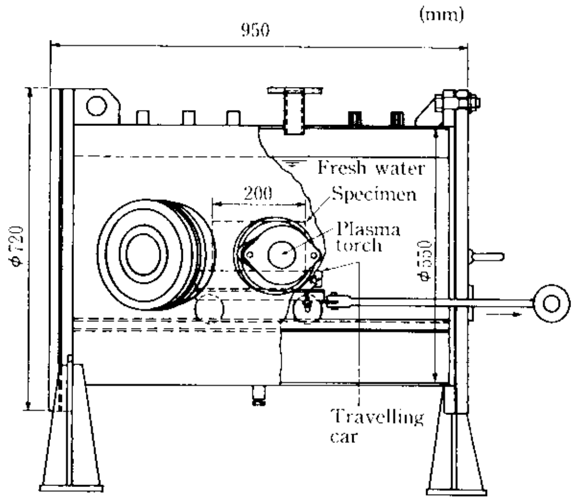

Fig. 4 Pressure tank

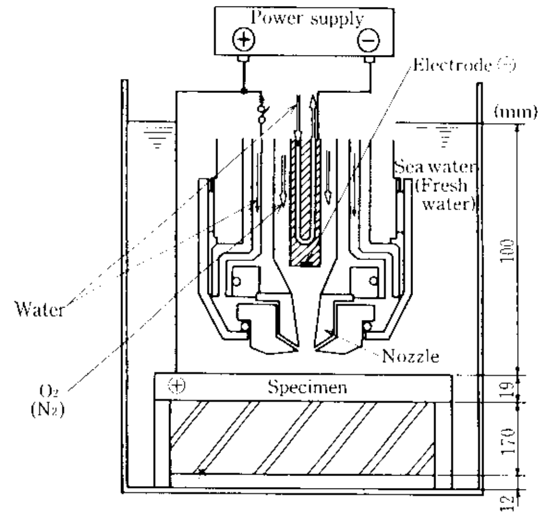

Fig. 5 Configuration of underwater plasma arc cutting experiment

were moved at speeds ranging from 500 to 3 000 mm/min to determine the maximum cutting speed for each thickness. The maximum thickness capable of being cut and arc voltages were then determined in sea water at a hydraulic pressure of 0.01 kgf/cm^{2}G by varying the standoff in the range of 5 to 27 mm while keeping the cutting speed at 1 500 mm/min.

The configuration of the tip of the torch nozzle is schematically shown in **Fig. 5**. The cutting method shown in this figure was used for the case when clay or sand exists behind a 19-mm-thick test steel plate. The box-shaped specimen contains clay or sand filled under pressure. Sea water was fed into the water tank so that the water depth of the torch became 100 mm. In this experiment, the same values for plasma gas, voltage, flow rate, and nozzle port diameter as shown in Fig. 4 were used, although the cutting speed range was different, ranging from 200 to 1 200 mm/min, and the torch was installed in a downward direction.

Ceramics are attached to the peripheral part of the tip of the used plasma torch nozzle and injection water spouts from the gaps between the ceramics and the nozzle during the cutting experiment.

3.2.2 Underwater cutting capacity

The relationship between cutting speed and the maximum steel plate thickness capable of being cut is shown in **Fig. 6** for the case where the water pressure changes when water (sea water) is used. The maximum steel plate thickness capable of being cut decreases with increasing cutting speed; it also decreases somewhat when the water pressure increases from 0.01 to 2 kgf/cm^{2}G. There is no noticeable difference in the cutting capacity between oxygen and nitrogen plasma gases. This can be explained by the fact that these two experiments have almost the same heat input per cut width (heat input/nozzle diameter).

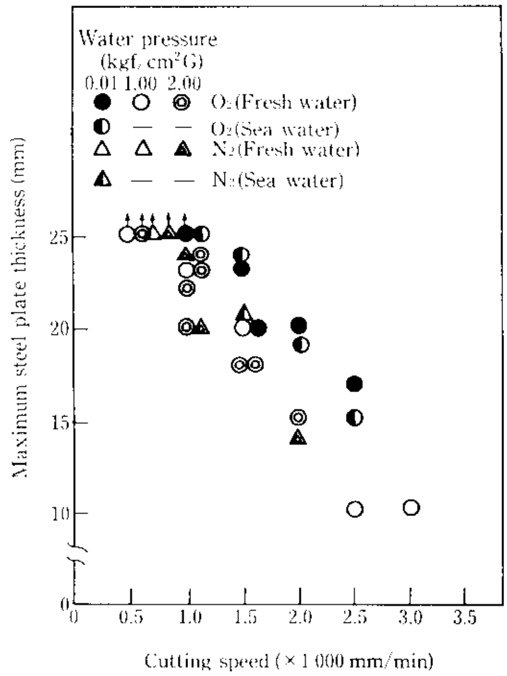

Fig. 6 Relation between torch cutting speed and maximum steel plate thickness for underwater cutting

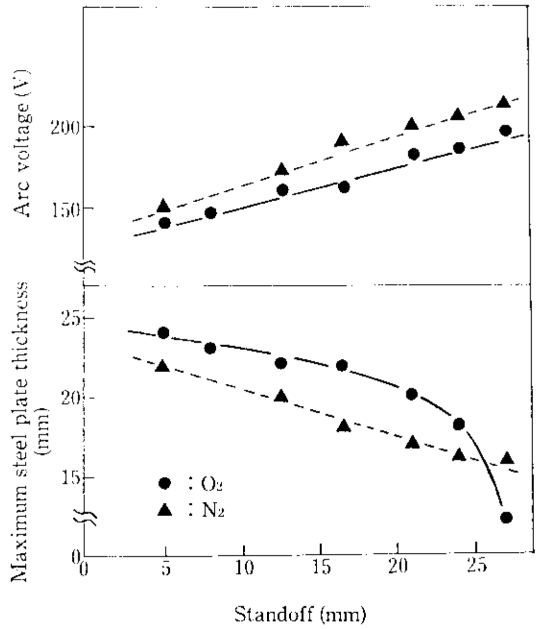

Fig. 7 Effect of torch standoff on plasma arc voltage and maximum steel plate thickness for underwater cutting

The dispersion of plasma energy usually takes place in sea water due to its good conductivity, and it is, therefore very difficult to put plasma cutting into practical use. In this experiment, there was no great difference in the effect of water quality at a water pressure of 0.01 kgf/cm^{2}G when tap water and sea water were used, because the configuration of the tip of the plasma torch nozzle (shown in Fig. 5) suppresses the formation of series arc that causes a decrease in the current density of the main arc. Specifically, this is due to the insulating effect of the ceramics attached to the periphery of the nozzle tip and the pinch effect of water in the nozzle. The pinch effect includes both a mechanical pinch effect caused by the copper nozzle and a thermal pinch effect produced by passing the injection water through the gaps between the periphery of the arc column and the nozzle, and as a result, the formation of series arc that moves through the nozzle is suppressed.

Effect of torch standoff on plasma arc voltage and the maximum plate thickness capable of being cut are shown in **Fig. 7**. While at a water pressure of 0.01 kgf/cm^{2}G, the standoff required when the pilot arc changes over to the main arc is 8 mm, cutting is possible even with a standoff of 27 mm. The arc voltage increases, however, and the maximum steel plate thickness decreases with increasing standoff. This decrease in the cutting capacity associated with an increase in the standoff is considered attributable mainly to an increase in the diameter of the plasma arc column and a decrease in the plasma jet velocity.

3.2.3 Cutting characteristic when clay or sand is present behind pipe wall

A cutting experiment was conducted for the case where clay or sand was present behind a 19-mm-thick steel plate in sea water. Results of the experiment are shown in **Fig. 8**. As schematically shown in the figure, the molten metal splashes back into the cut groove due to the effect of the dense clay or sand behind the steel plate and solidifies there. A complete cutting area free from this redeposited metal was present at the interface between the solidified metal and the cut groove at a cutting speed of 800 mm/min when nitrogen plasma with a current of 400 A is used, and at the cutting speed range of 400 to 600 mm/min with oxygen plasma and a current of 260 A. The shape of the groove showed excellent uniformity over the full length in the direction of cutting. This was due to the stable arc and flow of molten metal.

When the cutting speed is set at a low value of 200 mm/min for both nitrogen plasma and oxygen plasma, the arc becomes unstable, preventing the uniform flow of molten steel. As a result, a partial bridge is formed over the cut groove and the redeposition of the solidified metal occurs, making cutting incomplete.

When the cutting speed is set at a high value of 1 200 mm/min, the flow of molten metal becomes incomplete due to insufficient heat and the redeposited zone is formed locally.

It is desirable that the upper portion of the piles is drawn up easily after cutting, therefore, the redeposition

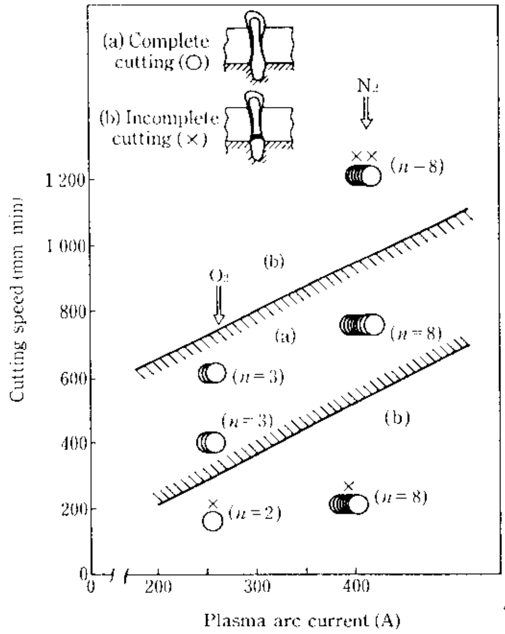

Fig. 8 Relation between plasma arc current and cutting speed

Table 2 Specifications of the newly developed underwater cutting machine

Pipe piles	
Diameter	800～1 200 mm
Thickness	9～25 mm
Diameter of junction	165.2 mm
Thickness of junction	9, 11 mm
Plasma arc device	
Arc current	100～400 A
Open circuit voltage	400 V
Gas	O_2, N_2
Torch travel speed	600～2 000 mm/min
Grinder device	
Diameter of grinder	500～650 mm
Cutting time	～10 min/junction
Sensors	
Position of grinder	Displacement sensor
Position of plasma torch	Encorder

of molten metal should be avoided. The oxidation proceeds more vigorously, both in the molten metal and on the cut solid surface with oxygen plasma, thereby preventing excessive redeposition, and the redeposited solidified metal separates under slight impact even when redeposition anywhere occurs. Appropriate conditions for the successful cutting method are therefore obtained using oxygen plasma.

4 New Underwater Cutting Apparatus–Plasma Cutter

4.1 Makeup of Apparatus

The underwater cutting apparatus is composed mainly of a plasma arc device and a grinder device. The main specifications of the apparatus are given in **Table 2** and a general view is shown in **Photo 1**. A pilot arc is generated in the plasma torch and changes over to the main arc. At the same time, the plasma torch is turned along the inner wall of the main pipe, which is cut by a plasma arc.

The grinder cutter is installed within the cutting apparatus, as shown in Photo 1, with the cutter fed toward the junction pipe when the pipe is to be cut. After one junction pipe is cut, the cutting mechanism is turned to cut the other junction pipe. During this process the section of the main pipe is only partly cut, therefore maintaining sufficient rigidity of the structure, and the problem of bite and stoppage of the grinder cutter is therefore prevented.

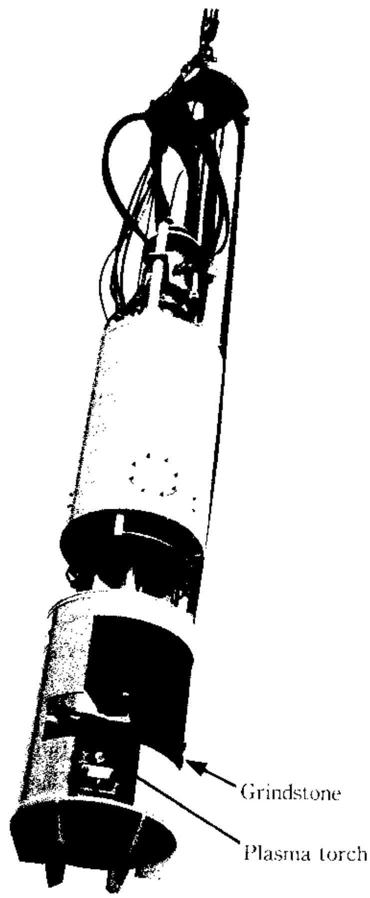

Photo 1 General view of the newly developed underwater cutting apparatus

4.2 Test of Cutter Performance

The performance of the newly developed underwater cutter was confirmed using an actual apparatus. The test method is shown in **Fig. 9**. The specimen consisted of two interlocked welded steel pipes 800 mm in diameter, 16 mm in wall thickness, and 6000 mm in length, to which junction pipes filled with mortar with a compressive strength of 240 kgf/cm^2 were welded. The specimen was placed in a 4-m-deep water pool. The cutting position of the specimen was located at points 2 to 3 m under the water surface and clay or sand was placed behind the steel pipes. In the plasma arc cutting, oxygen plasma was used and the cutting current was 260 A.

The results of this experiment are shown in **Table 3**. The time required for cutting was 18 min for two junction pipes and 2.7 min for one main pipe, a total of 21 min. Cutting with the grinder is shown in **Photo 2**, and cutting with the plasma arc is shown in **Photo 3**. The specimen after cutting was examined and it was determined as shown in **Photo 4**, that good alignment of the cuts of the junction pipes and main pipe was obtained.

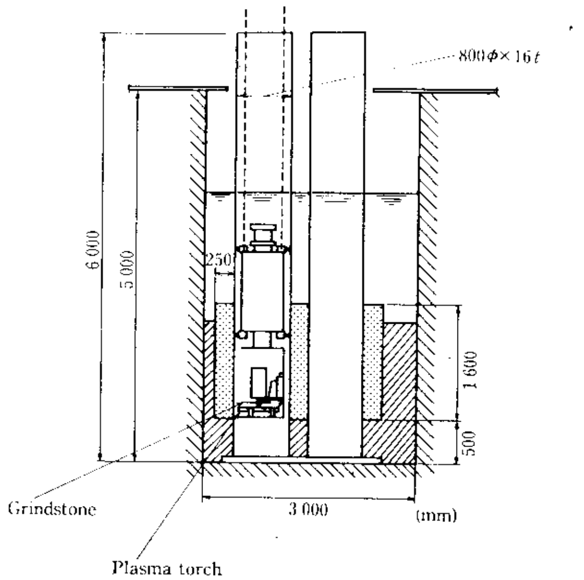

Fig. 9 Configuration of underwater cutting experiment using the cutting machine

Photo 2 Underwater cutting of junction pipe and main pile pipe by grindstone

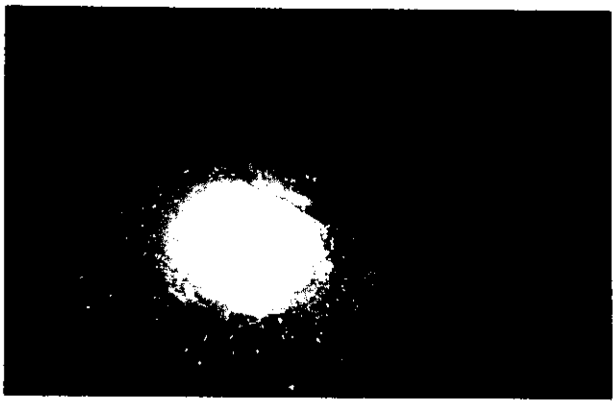

Photo 3 Underwater cutting of main pile pipe by plasma arc

Table 3 Underwater cutting test results for interrocked steel pipe piles (main pipe, 800 mmφ × 16 mm*t*, junction pipe, 165.2 mmφ × 9 mm*t*)

Test No.	Cutting device	Cutting object	Cut length (mm) Depth	Width	Circumferential	Cutting time (min)
1	Grindstone*1)	Junction 1*2	187	670		9.0
		Junction 2*2	172	630		9.0
	Plasma arc (O_2)	Main pipe			2 440	2.7
2	Grindstone*1)	Junction 1*2	166	649		8.0
		Junction 2*2	168	654		8.5
	Plasma arc (O_2)	Main pipe			2 440	2.7

*1 Grindstone blade: 610 mmφ × 6 mm*t*
*2 Junction pipes are filled with mortar.

Photo 4 Main pile pipe and junction pipes after cutting by plasma arc and grindstone

5 Conclusions

In order to establish a non-precut method for interlocked steel pipe piles used both as foundation support and as temporary dewatering cofferdams, fundamental experiments in underwater cutting were conducted and a new underwater cutting method and apparatus were developed by combining grinder cutting and plasma arc cutting. The main results of these experiments were:

(1) The power required for the rotation of the grinder cutter under water increases exponentially with increasing circumferential speed. For this reason, it is desirable that cutting be conducted at low speeds, unlike the high-speed cutting generally adopted in air.

(2) Even under tap water or sea water, the cutting speed of steel pipe using plasma arc is very high. When oxygen plasma at a load current of 260 A is used, it is possible to cut a steel pipe 800 mm in diameter with a 16 mm wall thickness in about 2 min.

(3) In this newly developed underwater cutting apparatus, it is possible to cut the junction pipes with a grinder cutter and the main pipes by a noncontact-type plasma arc. Cutting performance is excellent, and the junction pipes and main pipes can be cut under water very accurately at the same predetermined cutting level. Interlocked steel pipe piles 800 mm in diameter and 16 mm in wall thickness can be cut very efficiently at a speed of about 20 min per piece.

This underwater plasma cutter can be used for the high-speed underwater cutting of steel pipe piles in addition to the underwater cutting of interlocked steel pipe piles used in the non-precut method.

The authors would like to extend their sincere appreciation to staff members of the Shoei Ltd. for their cooperation in manufacturing the prototype of the underwater cutting apparatus.

References

1) M. Saito, T. Shiraishi, and S. Nonaka: *Kawasaki Steel Giho,* **8**(1976)2, 118
2) K. Kurita, F. Ichikawa, T. Tekemura, and T. Shiraishi: *Kawasaki Steel Giho,* **14**(1982)4, 120-129
3) M. Kusumoto: *Seitetsu Kenkyu,* No.306(1981), 58-69