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Development and Application of Ground Improvement Machinery Chain Conveyor Cutter

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Natural ground generally consists of various types of soils and each soil independently reacts with cementing materials. In order to realize uniform and stable soil ground improvement, it is preferable that the excavated soils are vertically mixed together as a whole. Chain Conveyor Cutter (CCC) is like a chain conveyor but is installed vertically on a pile driver, sunk into and is raised up from the ground. An 180 kw water cooled electric motor rotates chain units and enables CCC to cut harder soils at the bottom of the machine discharging cement slurry. The soils and cement slurry are hauled up by the scraper bars of the chain units being mixed together on the way up to the ground surface, which consequently establishes stable improved ground.

1. Introduction

Conventional ground improvement machineries are represented by auger type machineries. Mixing paddles are attached on the edge of drilling rods and cutting bits are mounted on the bottom paddles. The assembly of a rod and mixing paddles with cutting bits called cutting head is rotated and sunk into the ground. The cutting head excavates the soils in situ and cement slurry is discharged through the port installed on the head. The excavated soils and discharged cement slurry are mixed together. The sinking speed of the cutting head is managed at most 50 cm per minute considering the mixing abilities of the cutting heads, so that the vertical movements of cut soils are limited and the soils are remained at vertically original position with mixed cement called soil-cement.

The physical properties of soil-cement depend on the soil types and cement mix design. There occur various types of soils in natural grounds and also in artificially reclaimed grounds. The strengths of soil-cement are governed by the weakest strata and the impermeability of the soil-cement walls are by coarse materials. With respect to the cement mix design, the volume of cement every 1 cubic meters of soil in situ is determined based on the weakest strata and/or most permeable strata which require the largest amount. The volume of water is also designed based on the mixing properties of strata. Cohesive clayey strata are sticky and require extra amount of water.

The cutting ability of the conventional auger type machineries is limited that the available ground conditions are limited to more or less 20 in N value. When those machineries come across harder ground, different auxiliary measures have to be taken. In case the machinery manages to penetrate the harder grounds, drilling rods tend to deviate due to their low rigidity, especially in the case of gravel rich grounds, which requires deliberate and skillful operation.

The cross section of soil-cement column constructed by the conventional auger type machineries is circular. Using circular columns, independent circular columns, walls, grid patterns and entirely improved grounds are constructed. Considering the column walls, for instance, the wall thickness is not constant and peripheral part of the circular column is in vain.

Ground improvement works with conventional auger type mechanical soil mixing is indispensable but contains intrinsic disadvantages as mentioned above. The ground conditions available for the conventional auger type machineries are therefore restricted from the view points of their mixing and cutting abilities.

On the other hand, chain saw type machine was developed and has been put into use specifically for constructing continuous underground walls. The working method using chain saw type machine is named Trench Cutting Re-mixing Deep Wall Method (TRD)[1].

The machinery TRD consists of a main body, a shifting apparatus and a hydraulic unit and is exclusively used for the continuous and straight wall construction, not for single columnar shaped structures. The main body is placed underground and horizontally moves forward while cutting and mixing the soil in situ with cement slurry which is discharged at the bottom of the machine. The TRD wall is same in thickness and has vertically uniform properties. The maximum depth of the wall reaches 50 meters. The machine TRD is special purpose machine for constructing underground straight continuous wall. Then, longer the wall is, the more cost effective. But TRD method is ineffective for constructing discontinuous ground improvement works like independent columns, grid patterns and polygonal walls.

To make up for the disadvantages of the TRD, Chain Conveyor Cutter (CCC) was developed for both continuous and discontinuous ground improvement works making use of the technology of underground coal mining equipment and experiences[2]. CCC is like a Chain Conveyor but is installed vertically on a pile driver and is sunk into the ground. An 180 kw water cooled electric motor enables the machine to cut harder ground at the bottom of the machine with cutting bits on the chain units and rotating chain units mix the soil. The soil and cement mixture is hauled up by the scraper bars and consequently vertically uniform rectangular columns are established.

2. Development of CCC

2.1 Concept of CCC

Concept of CCC is to establish quality oriented ground improvement and safe and flexible operation. The quality of the ground improvement includes uniformity of the improved bodies, low cement consumption, saving waste materials and the days to be worked, which require strong cutting ability, vertical mixing mechanism and rigid body of the machine.

Ground improvement machineries generally deal with soft grounds. The soft grounds ordinary consist of soils of less than 20 in N value. But, natural grounds are not necessarily uniform and soft enough to deal with. Artificial reclaimed grounds are likely to contain various materials. It is not always natural gravels and boulders but also manmade materials like debris of concrete.

Unexpected ground movement could hold the machine. CCC is to be provided sufficient driving power and durability for enabling the machine to afford versatile ground conditions and cost effective performances.

2.2 Chain conveyor

Chain Conveyor is commonly used for transporting materials like coal at production faces in underground coal mine. Fig. 1 shows a chain conveyor installed in longwall mining face. The transportation capacity of current chain conveyors exceeds more than 1,000 tons per hour and the conveyor length is more than 200 m. Short link chains are adopted and twin strand chain system is preferred. According to the running position, twin strand system is classified into outboard or center type chain system. Chain connectors are well developed and supporting high capacity transportation system.

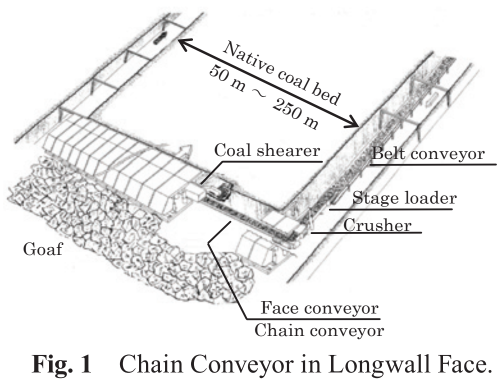

Fig. 1 Chain Conveyor in Longwall Face.

Drive units are electric motors located head end and, if necessary, tail end. In the actual operation of mining faces, the chain conveyor is forced to start running under fully loaded condition. In such cases, the starting torque reaches more than 200% of nominal torque. Once the conveyor succeeds starting, the torque decreases drastically. This characteristic driving performance is essential for CCC considering the unexpected hard materials to come across and irregular ground movements.

2.3 Roadheader

Ground improvement machinery generally deals with soils and cutting ability of such machineries are limited to more or less 20 in N value. But, ground improvement works include adverse conditions like gravel rich ground and artificially reclaimed land where unpredictable materials could occur. Coal and rock cutting machinery presents useful design criteria of chainsaw type machine.

Roadheader is one of the typical coal and rock cutting machinery first developed in 1950s for roadway drivage and coal winning works in coal mine. Nowadays, roadheaders are widely applied to soft to medium strength rock cuttings in mining and tunneling operations[3] (Fig. 2).

Considering the CCC cutting design, the cutting forces and normal forces of the roadheaderes present universal standard. According to the figures presented, the cutting force of 150 kN and the normal force of 200 kN are considered key forces to handle hard materials.

Fig. 2 S300M Roadheader.

2.4 Prototype CCC (Fig. 3)

Applying the subsidy of Omuta City, Fukoka Pref. Japan, a prototype CCC was developed in 2000. The specification and main structure of the CCC are as follows:

1) The CCC consists of a driving unit, a middle section and a return unit from the top of the machine in descending order.
2) The cutting depth is 10 m and a cross section of cutting area is rectangular 0.75 m wide and 1.0m long.
3) The capacity of a drive motor is 55 kW and planetary gearing system is adopted making use of its reliability and compact design.
4) The drive unit is located on the upper most part of

the machine when installed on the pile driver. The power is transmitted through the drive sprocket wheel to twin outboard chains which are connected by the connecting plates (scraper bars). On each scraper bar, a bit plate is mounted where the conical shaped cutting bits are installed with designed arrangement, which is called bit unit. Fig. 4 conceptually explains the bit unit of CCC.

5) A chain tensioning system is equipped and a set of pulleys are mounted on top of the drive unit for lifting the body using a main hoist of the pile driver.
6) On the side of the drive unit, a connecting apparatus is attached to allow smooth movement on the leader post of the pile driver.
7) The middle section consists of four middle posts designed rectangular shape. For preventing the snaking of the chain units and for lifting the soil and cement mixture, plates are welded at both sides of each middle posts.
8) Abrasive wear proof steel plates are adopted for the pan of the conveyor trough.
9) The middle posts are connected with bolts each other and two parallel 50 A pipelines are installed inside the posts to pump cement slurry or other materials from the inlet port placed upper post down to the discharge port placed on the return unit.
10) Specially designed pipe joints are adopted for preventing the leakage of pumped materials.
11) On the side of each middle post, tubular guide rails are mounted to connect with a guide holder equipped at the bottom of the leader post of the pile driver.
12) The return unit is located at the bottom of the machine. The cutting bits mounted on the bit plate cut the soils while running along the return unit as shown in Fig. 5. Faster the CCC is being sunk and/or harder the soils, severer impact loads are generated. The elements of return unit are given sufficient strength and durability and the sealing system is designed tight enough against soil and cement slurry mixtures.

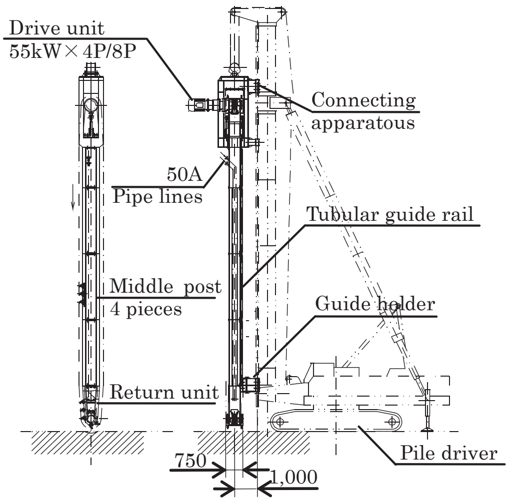

Fig. 3 Assembly Drawing of Prototype CCC.

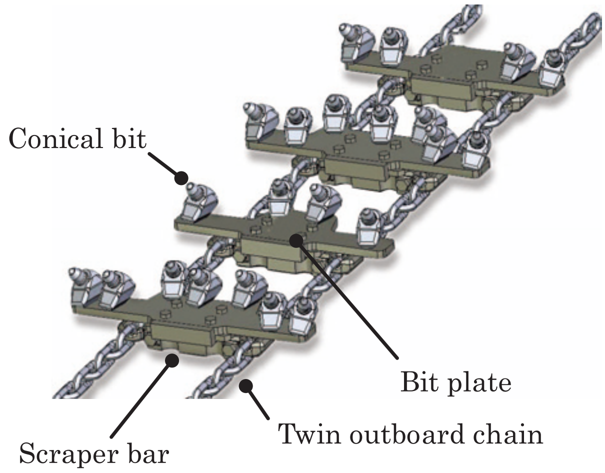

Fig. 4 CCC Bit Unit.

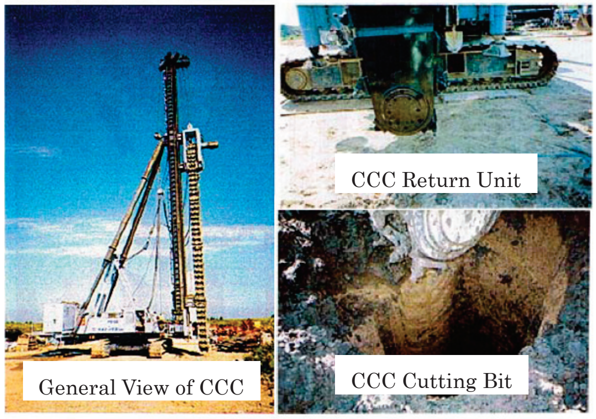

Fig. 5 Prototype CCC at Site.

2.5 First trial work

In the same year 2000, the first trial work was carried out using prototype CCC and four soil-cement columns were constructed without any trouble. Fig. 5 shows the prototype CCC at the first working site.

In this first trial work, the cement factor was 200 kg/m^3. The boring cores taken from different depth of each column showed the uniformity of the mixture of soil and cement and the uniaxial compressive strengths (UCS) satisfied predetermined target of 1.0 N/mm^2 as shown in Table 1.

Table 1 UCS of the Column (N/mm^2)

Depth (m)	Column 1	Column 2	Column 3	Column 4
2	6.4	4.4	4.1	4.0
4	6.2	8.0	3.3	2.6
6	7.8	9.5	2.3	1.8
8	-	6.8	2.3	1.3
10	-	7.9	2.0	2.0
Water/Cement (%)	100	100	200	200

2.6 Crane version CCC

Based on the first trial work, a crane version CCC was developed assisted by Ariake National College of Technology in 2003 (Fig. 6).

In the case of conventional auger type machineries, horizontal rotation requires rigid holding apparatus to resist counter force of the rotating cutting head. The vertical movement of CCC does not generate horizontal moment that the crane version of CCC was considered feasible. The joint study and test work titled “Compact Lightweight and Multi Purpose Type Ground Excavator CCC” proved the feasibility of crane version CCC.

Fig. 6 Crane Version CCC.

2.7 High power CCC (Fig. 7)

Subsequently, the development works of a commercial base CCC named “High Power CCC” (HCCC) were commenced and the first machine was manufactured in 2005. The specification of HCCC is compared with CCC in Table 2.

Fig. 7 High Power CCC.

Table 2 Specifications of CCC and HCCC

	CCC	High power CCC
Drive motor	55 kW air cooling	180 kW water cooling
	Direct online start (Pole change)	Inverter drive (Variable frequency drive)
Machine length	16 m	28 m
Machine weight	23 ton	28 ton
Shape of excavation	Rectangular 0.75 m^2	Rectangular 0.9 ～ 1.2 m^2
	0.75 m×1.0 m	0.75 ～ 1.0 m ×1.2 m
Depth of excavation	10 m	20 m
Chain type	Twin outboard 19 mm ϕ	Twin outboard 22 mm ϕ
Chain tension	7 ton	23 ～ 60 ton
Chain speed	25 or 50 m/min	0 ～ 60 m/min

2.8 Field application and machine modification

The records of HCCC field application and the machine modification are as follows:

1) In October 2005, HCCC excavated underground continuous walls constructed by prototype CCC in 2003 in order to return leased land to Omuta City.
2) In April 2006, HCCC was applied to the test excavation of the concrete mass at Noda City, Chiba Prefecture.
3) In June 2006, HCCC attended the test work of withdrawing concrete piles already installed underground at Nagano City, Nagano Pref.
4) The UCS of the wall at Omuta City and the concrete mass at Noda City were 3 N/mm^2 and 27 N/mm^2 respectively. The sandy sediments surrounding the concrete piles at Nagano City contained a lot of hard gravels. The conditions of these three working sites were beyond the ability of conventional auger type machineries. HCCC showed the feasibility under adverse conditions but presented a new problem on the return unit. Then the return unit was redesigned and manufactured.
5) In 2007, HCCC constructed impermeable walls and destructed the walls constructed by HCCC itself. The specification of the walls was 0.85 m thick, 8 to 9 m deep, total 311 m long and the overall wall area was 2,700 m^2.
6) The working condition of the site was much worse than expected and HCCC suffered severe damages due to the obstacles like PC piles and reinforced concrete structures. These damages made it clear that more sophisticated chain speed control system and modifications of bit arrangement are inevitable for more smooth and effective bit attacks to the soils in situ. As a chain speed control system, inverter

drive system (variable frequency control system) was developed and introduced to HCCC. The inverter control system enabled HCCC non step continuous chain speed control which is of great help for safe and sound operation.

2.9 Summary of HCCC structure and movement

Summarizing the above, the structure and movement of HCCC are as follows. As shown in Fig. 8, HCCC consists of a drive unit, a middle section and a return unit from the top of the machine in descending order. The drive motor is 180 kW inverter drive and middle section consists of a number of posts according to the depth of the ground to be improved. The cutting depth is up to 20 meters. The cutting bits cut the soil while running along the return unit. While HCCC is being sunk discharging cement slurry, the cutting bits run at maximum 60 meters every minute (Fig. 9). The scraper bars connecting twin outboard chains scrape up, agitate and mix the cut soil with cement slurry, which is named “conveyor effect”. There exists only small room for the soil and cement that “conveyor effect” works and the soil and cement is raised up to the ground surface.

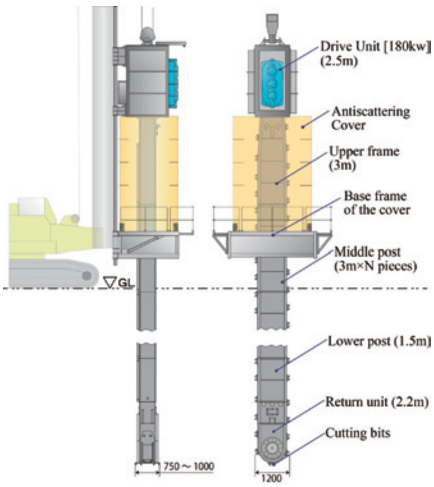

Fig. 8 Conceptual Diagram of HCCC.

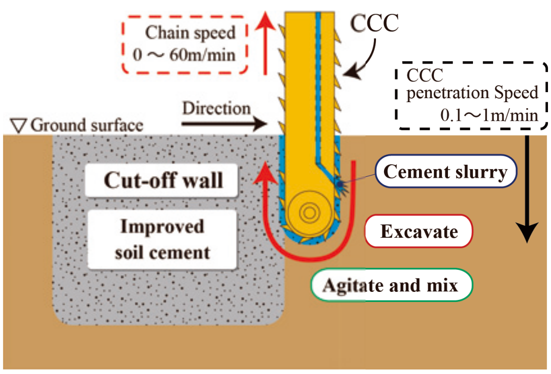

Fig. 9 Conceptual Diagram of HCCC Movement.

On the other hand, scraper bars running down to the return unit convey raised soil and cement slurry down to the ground. Once HCCC reaches to the predetermined depth, slurry pump is stopped, CCC is raised up to the surface and the void is filled with the mixture of soil and cement. As a whole, the soil and cement behaves complicated movement which enables CCC to establish high quality improved bodies.

3. Working record of HCCC

In Feb. 2007, the planning subcommittee of the port deliberation council in the Ministry of Transport approved the Port of Miike Restoring Plan which contains widening and deepening shipping lane of the port. According to the plan, restoring work was started and two settling ponds were constructed for receiving and treating dredged materials.

HCCC constructed cut-off walls surrounding the ponds to block water seepage from inside the ponds. The land, where the ponds were constructed, was reclaimed by Miike Coal Mine, closed in 1997. Therefore, the ground consists of natural rocks like sandstone, shale and silicate fossil rocks. Those rocks were weathered but still maintain the strength and porosity as a whole. Fig. 10 shows typical columnar sections of the ground where hard materials exceeding 50 in N value are observed.

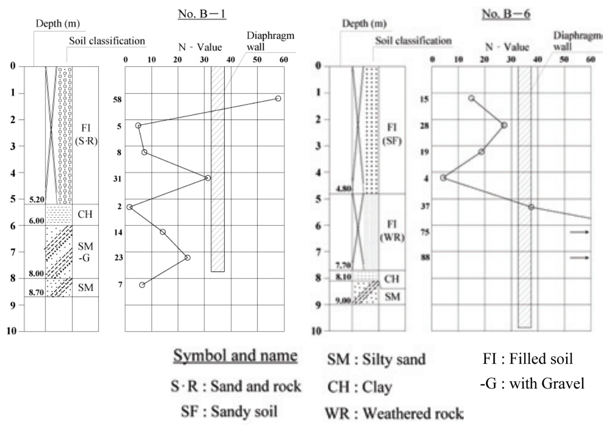

Fig. 10 Typical Columnar Sections of the Ground.

3.1 Method of wall construction

Under these difficult ground conditions, the time and cost available for constructing cut-off walls were limited and the land owner wanted to re-use the land afterwards. Conventional sheet pile walling is one of the methods but was not applied to this site due to the existence of hard materials and considering the re-use of the land. Conventional auger type method is difficult to handle hard ground.

In 2007, HCCC constructed cut-off walls and removed those walls by itself at the neighborhood of the proposed site. Evaluating this result, HCCC cut-off walling was selected.

3.2 Working record

The reclaimed land consists of weathered coal mine origin rocks placed directly on the sea floor.

The sea floor is thick clay rich seams named Ariake Nendo Seam which is considered impermeable having the hydraulic conductivity of more or less 1×10^{-6} cm/sec. Japanese standard defines the hydraulic conductivity and thickness of the impermeable ground of the landfill site as 1×10^{-5} cm/sec and 5 m respectively[4)]. The hydraulic conductivity and thickness of the Ariake Nendo Seam at site satisfied the landfill standard. Then, the cut-off walls were designed to penetrate into the sea floor and the requested hydraulic conductivity and the wall thickness are 1×10^{-6} cm/sec and 0.75 m respectively based on the standard of final landfill site of Japan.

The specification of the first pond was 0.75 m thick, 7 to 8 m deep and 1,128 m long in total. The overall area was 8,470m^2. That of the second pond was 0.75 m thick, 8 to 10 m deep and 1,197 m long and the total area was 10,420 m^2. Laboratory tests were conducted using boring cores taken at site and the mix design was decided as follows:

1)	Type of cement	Blast furnace cement
2)	Cement factor	1st pond 150kg/m^3
		2nd pond 200kg/m^3
3)	Water/cement ratio	1st pond 150%
		2nd pond 100%

The productivity of HCCC works was approx. 200 m^2/day and the core samples taken from the constructed wall satisfied the design value as shown in Figs. 11 and 12.

4. Functions of HCCC

4.1 Flexible cutting method

HCCC is equipped with an inverter drive 180 kw electric motor and the chain unit is driven by the pulling force of max. 55 ton. Fig. 13 explains HCCC cutting method of constructing continuous soil-cement body, like cut-off wall, square block body, etc., but not single column. Ordinary cutting method laps each unit for 20 cm and an effective advancement is 1 m. When the working ground is hard and is not advantageous to lap 20 cm, HCCC changes the laps and decreases the cutting resistance as shown in Fig. 13 in order to maintain productivity.

In addition to the variable chain speed and strong cutting force, the flexible cutting method enables HCCC to apply difficult ground conditions and to excavate and restore improved soil-cement bodies.

4.2 Soil replacement

Besides constructing soil-cement improved bodies, HCCC replaces soils in the ground. Fig. 14 explains the sequence of HCCC soil replacement. When HCCC is penetrated into the ground without discharging slurry, soils cut by the running bits around the return unit, at the bottom of the machine, are lifted up to the surface utilizing conveyor effect.

On the other hand, filler soils are charged while HCCC is raised up to the surface. The conveyor effect works and the filler soils are moved down to the bottom of the machine. When HCCC reaches on surface, the void excavated by HCCC is filled with filler soils and the soils are completely replaced.

Sand columns are well established using this function which is considered effective as one of the preventives of ground liquefaction.

When considering ground improvement works, this function is helpful for designing physical properties of improved soil-cement bodies. Organic soils, like peat, are generally difficult to improve and requires high cement factor[5)], amount of cement added to unit volume of the ground. By changing the composition of the original ground, withdraw some part of original ground and add soils from outside, various types of soil-cement bodies are constructed. The mix design is to be conducted based on the required properties like strength or permeability by mixing original soils and filler soils together, which is new concept of the mix design.

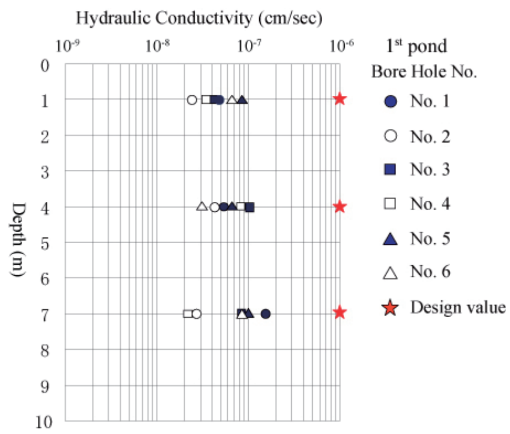

Fig. 11 Hydraulic Conductivity of the 1st Pond.

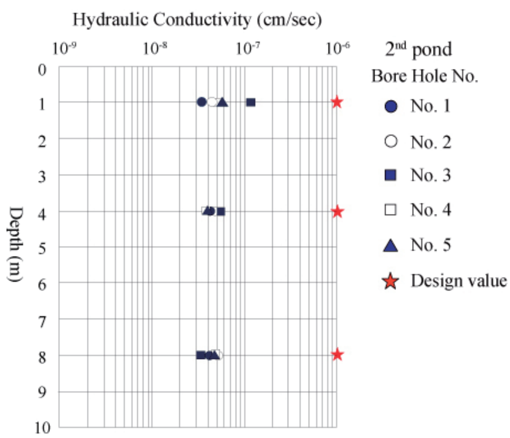

Fig. 12 Hydraulic Conductivity of the 2nd Pond.

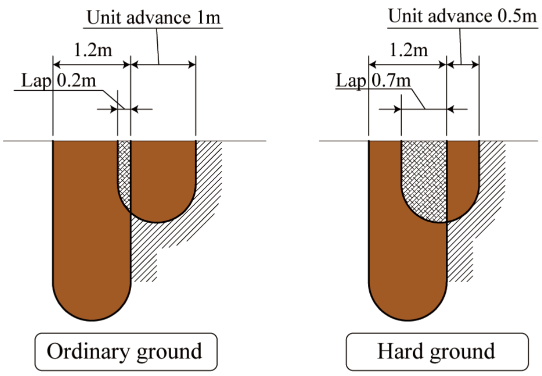

Fig. 13 HCCC Cutting Method.

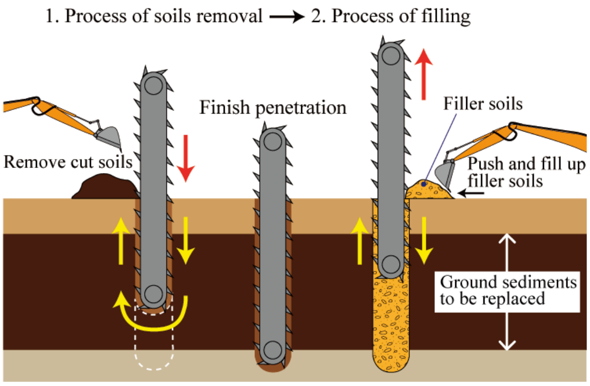

Fig. 14 HCCC Replacement Method.

5. Prospect to the Future

Making use of the characteristic cutting and mixing abilities and its conveyor effect, various types of soil-cement structures are expected. Fig. 15 is one of the concepts for constructing final landfill site on the ground. At first, HCCC construct artificial impermeable soil-cement ground using original ground. After constructing embankment on the artificial impermeable ground, HCCC construct water tight wall in the embankment. This landfill site can be combined with sheeting system. Such hybrid system is located above the original ground level, so that water leakage from embankment is directly observed if happens. The basement of landfill is constructed not only water tight but also seismic resistant, which is advantageous for reuse of the final landfill site.

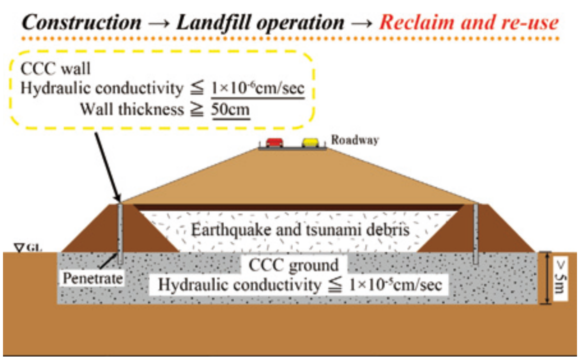

Fig. 15 Conceptual Diagram of HCCC Landfill Site.

The U.S. Environmental Agency published a report on Permeable Reactive Barrier (PRB) technologies for contaminant remediation in 1998[6]. Fig 16 shows one of the PRB systems named funnel-and-gate system. The funnel-and-gate system consists of funnels and gates.

The impermeable funnels lead polluted groundwater (GW) flows to permeable gate where reactive materials are placed. The flexible cutting method and the function of material replacement are available for constructing PRBs and emplacement of reactive materials into the reactive gate. When applied to PRB construction, HCCC construct water tight funnel walls and a gate block using soils in situ and cement first, as shown in Fig. 17. Then, HCCC excavate the solidified soil-cement gate block and fill the void with reactive materials. This way of thinking, funnel and gate system, is applicable to landfill site inspection wells. If inspection wells are combined with funnels, funnels collect leachate to the well and wider area is monitored by each well, which will improve the safety and the reliability of the final landfill site system.

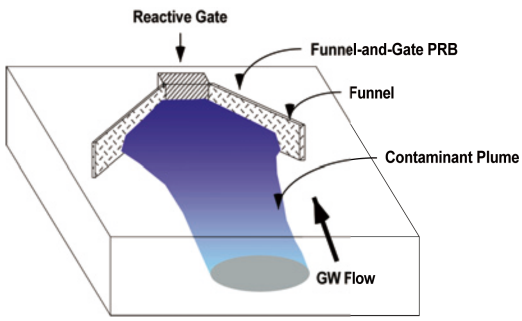

Fig. 16 Conceptual Diagram of Funnel-and-Gate.

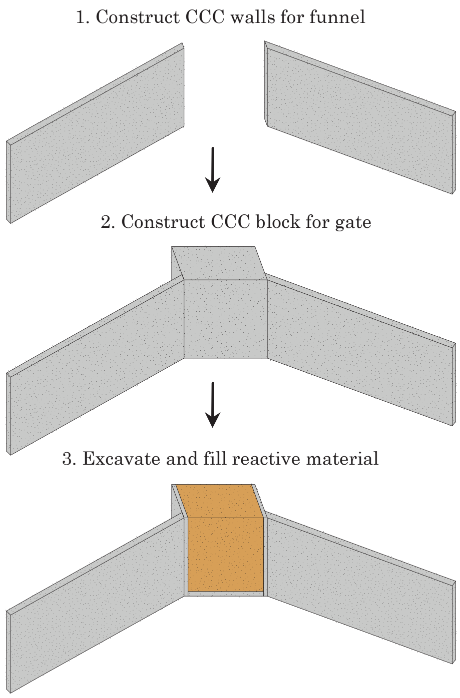

Fig. 17 Sequence of CCC Funnel-and-Gate construction.

6. Conclusions

Chain saw type ground improvement machinery CCC constructs high quality soil-cement body using vertical cutting and mixing functions. Conveyor effect plays important roles for preventing entrained soil circulation and for maintaining uniform mixing. Cutting bits cut soils at the bottom of the machine while travelling around the return unit. The cutting force is utilized by the limited number of bits around the return unit that hard soils exceeding 50 in N value is workable, which enables CCC to restore improved soil-cement bodies.

The function of replacement is helpful for improving difficult soils like peat and saves the cement consumption.

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References

1) M. Mizutani, *Kobe Steel Engineering Report*, **57**(1), 96 (2007).
2) H. Furukawa, *Journal of MMIJ*, **105**(11), 808 (1989).
3) N. Kashiwamura and K. Sasaki, *Journal of MMIJ*, **106**(11), 636 (1990).
4) Ministry of Health, Labor and Welfare, Ministry of Internal Affairs and Communications, *Amendment Order of Technical Standards in terms of Non-industrial and Industrial Disposal Final Landfill Site*, 16th June, 1998. (in Japanese)
5) Public Works Research Center, *Design and Operation Manual of Deep Mixing Method for Land Works*, Revised Edition, p.35 (2004). (in Japanese)
6) United States Environmental Protection Agency, *Permeable Reactive Barrier Technologies for Contaminant Remediation*, EPA/600/R-98/125 (1998).