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Development of Chain Conveyor Cutter Method and Its Application

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Abstract— Currently, ocean disposal sites can provide more space for landfill than other areas such as waste landfill in the mountains and in the coastal areas. The construction of disposal sites in the ocean, therefore, has received attention in Japan, which has limited space for landfill. In the case of ocean disposal sites, the leakage of pollutants from waste materials has to be prevented by constructing a vertical impermeable wall around the disposal site.

In the field of ground improvement works, mechanical soil mixing is an indispensable technique and is carried out using an auger type machine with mixing paddles attached to the drilling rods. This type of machine excavates the soil in situ horizontally and cannot mix the cut soil vertically. In this system, the strength of the constructed soil cement column is governed by the weakest strata and the impermeability of the constructed soil cement wall is not necessarily uniform. From this point of view, the Chain Conveyor Cutter (CCC) method has been developed as the technology for soft-ground stabilization in Japan. The ground is excavated with the construction of an improved wall by injecting a fixation agent in the method. It is expected that this method will be utilized for the construction of an impermeable wall in ocean disposal sites due to low cost and the simplicity of the construction process.

This paper presents a comparison of the performance of a vertical impermeable wall constructed using the CCC method and another using the conventional method through the simulation of the spread of contaminants from the waste storage area with two-dimensional advection-dispersion program, Dtransu-2D, with the aim of the application of the CCC method to the construction of ocean disposal sites. The results indicated that the CCC method can be applied to the construction of ocean disposal sites, enabling the construction of an impermeable wall in a simple way and at lower cost when compared with walls that were constructed using the conventional method. Additionally, the distance between the impermeable wall and the waste storage area in ocean disposal sites should be larger in order to minimize the effect of water flow near the impermeable wall on the spread of pollutants from the waste storage area.

Keywords: Chain Conveyor Cutter (CCC), Ocean Disposal Sites, Advection-dispersion, Dtransu-2D.

1. Introduction

Mitsui Miike Coal Mine was the largest mine in Japan and closed in March 1997. The mine extracted coal in the underground beneath the Ariake inland sea for more than 100 years and developed advanced technology in the field of coal winning, tunneling and so on. As shown in Figure 1, Mitsui Miike High Power Plant (MHP) was introduced in 1988 for realizing the average daily output of 6,000 tons by allowing a peak capacity of 10,000 tons of coal per day and contributed until the closure of the mine, maintaining the safety of the mine.

Figure 1. Underground machinery MHP

Based on the accumulated technology of coal mining in Miike, the authors have collaborated and developed new types of machines for improving soils in situ named Chain Conveyor Cutter (CCC) and the CCC method has enabled us to develop new types of effective working methods. The CCC was introduced into public works this year for constructing impermeable walls surrounding large settling ponds for preventing the water from flowing out through the bottom of the ponds and successfully finished the works. This paper describes the development works of the CCC and the working method utilizing the CCC.

2. Characteristics of Underground Mining Machineries

Notable differences exist in the working conditions between the machineries in underground use and the earth moving machineries used on surface.

The spaces available for the underground machineries are limited, and the combustible gas emitted from the coal seams require extra safety considerations. The characteristics of underground machineries and the know-how employed for designing and manufacturing the CCC are summarized as follows:

1) The advanced mining machineries are systemized and require the harmony of each element.
2) In spite of the limited space, the machineries must be robust, heavy duty, powerful and flexible enough to follow the changeable mining conditions such as thickness, dip and hardness of coal, geological fault etc.
3) The power required to operate the electric motors is sometimes more than 200% of nominal output for a short duration of time like starting the conveyor of the working face due to fallen coal or rocks. The torque distribution curve of the machine is very characteristic and is useful for designing the CCC.
4) Methane gas is combustible and requires the electrical equipment be flameproof and is controlled by sensors.
5) In addition to the methane gas emission, the water sprayed for dust suppression prohibits the electrical and/or mechanical chambers to be opened to the atmosphere due to the loosening of packing bolts caused by the severe vibrations accompanied by the operation itself.
6) The sealing techniques are indispensable for the machineries that the techniques utilized are adopted.

3. Application of CCC method to Construction of Ocean Disposal Sites

An ocean disposal site is considered one of the best ways to treat a large volume of waste. It has received attention due to a rapid increase in the amount of waste produced in Japan. The performance of an impermeable wall to prevent the leakage of contaminants from the waste storage area is the most important parameter in ocean disposal sites. The vertical impermeable wall is usually constructed by the soil improvement; however, it is difficult to construct the wall using conventional methods under the condition that the ground is hard. In order to construct the impermeable wall via soil improvement, the CCC method was developed, and it is highly expected to be applied to many cases such as ground improvement and the construction of impermeable walls as shown in Figure 2 [1].

Figure 2. Chain Conveyor Cutter (CCC).

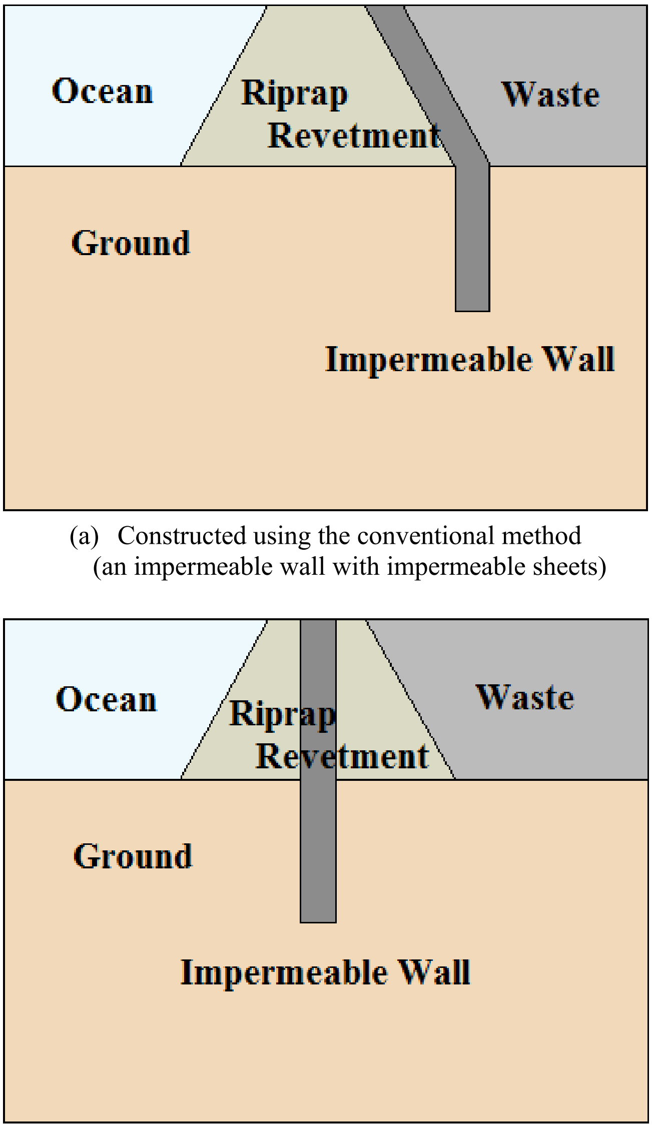
The CCC method utilizes a pile driver even if it is a chain saw type. This method was established in order to perform a variety of construction by taking the equipment body in and out in the same manner as the auger type. In this method, the soft ground is strengthened by mixing the soils and cementing materials which are injected into the ground from the top of the chain through the agitation and the mixing process. The advantages of this method are described as follows:

i) Vertically homogeneous ground is formed by mixing the soils and the cementing materials in a vertical direction.
ii) Continuous wall of equal thickness is constructed by the CCC method since the cross-section of improved area becomes a rectangular cross-section due to the cross-sectional shape of the equipment.
iii) Its versatility and high economic efficiency

When an impermeable wall is constructed in ocean disposal sites, the CCC method is useful for the construction since it allows us to construct the wall which strength and permeability are homogeneous in a vertical direction [1].

In the conventional method, an impermeable wall is constructed under the ground before the construction of the embankment, followed by the construction of an impermeable wall along the slope of the embankment as shown in Figure 3(a). Thus, caisson type, slope type, sheet pile type, and the combination of them in Figure 3(a) have been introduced to the embankment in ocean disposal sites [2]. On the other hand, when the CCC method is applied to the construction of ocean disposal sites, an impermeable wall is constructed through the revetment and the ground after the construction of the revetment as shown in Figure 3(b). The difference in the structure of the impermeable wall in Figures 3(a) and (b) may result in the change in performance of the impermeable wall. In order to apply the CCC method to the construction of the impermeable wall in ocean disposal sites, the performance of the impermeable wall constructed using CCC method has, therefore, to be compared with walls constructed using the conventional method.

In this paper, the leakage of contaminants from the waste storage area in ocean disposal sites was simulated with Dtransu-2D, which considers advection and diffusion of pollutants, aiming at comparing the performance of the impermeable wall constructed using the CCC method and the conventional model. Based on the results, the application of the CCC method to the construction of the impermeable wall in ocean disposal sites was discussed.



(a) Constructed using the conventional method (an impermeable wall with impermeable sheets)

(b) Constructed using the CCC method

Figure 3. Schematic view of the ocean disposal site

4. Analysis for application of construction of ocean disposal sites

4.1. Analysis model

Figure 4 shows a schematic view of the analysis model, and the input parameters are listed in Table 1. The model was set at 50 m in height and 110 m in width, and the riprap revetment with a 10 m height was set between the ocean area and the waste storage area as shown in Figure 4. The ground was set until 40 m depth, and the impermeable wall was embedded into the ground. Whereas the impermeable wall constructed using the CCC method was set as illustrated in Figure 4, the wall constructed by the conventional method was set along the slope of the embankment as shown in Figure 3(a). Additionally, the combination of the impermeable layer and an impermeable wall was set at the slope of the embankment in the disposal site constructed using the conventional method. The impermeable layer was composed of the protection mat, the impermeable sheets, and the backfilling materials as described in Figure 5. The layer composed of alluvial clay with 40 m in thickness was set up as the ground II under the layer composed of alluvial clay with 10 m in thickness which was set up as the ground I, as illustrated in Figure 4. The permeability of the ground I and II was set at 1.0×10^{-4} cm/sec and 1.0×10^{-5} cm/sec, respectively. The impermeable wall was embedded into the ground II until 2.5 m depth in the disposal sites constructed by the conventional method and the CCC method. The difference in hydraulic head between the ocean area and waste storage area was set at 1.0 m. The leakage of contaminants from the waste storage area was simulated for 50 years in the models. These input data was determined by reference to the past studies as summarized in Table 2 [2,3].

Table 1 – Physical properties of the impermeable layer

	Permeability (cm/sec)	Thickness (cm)
Impermeable wall	1.0×10^{-6}	100
Impermeable sheet	1.5×10^{-9}	0.3
Backfilling material Protection mat	1.0×10^{-3}	0.5

Table 2 – Input data

Permeability (cm/s)	Ground I	1.0×10^{-4}
	Ground II	1.0×10^{-5}
	Impermeable wall	1.0×10^{-7}
Effective porosity (-)	Ground	0.4
	Impermeable wall	0.1
Specific storage (1/m)		2.0×10^{-5}
Longitudinal dispersion (m)		1
Transverse dispersion (m)		0.1
Coefficient of molecular diffusion (cm^2/sec)		1.0×10^{-9}
Tortuosity (-)		0.5
Retardation coefficient (-)		1
Adsorption coefficient (1/sec)		0

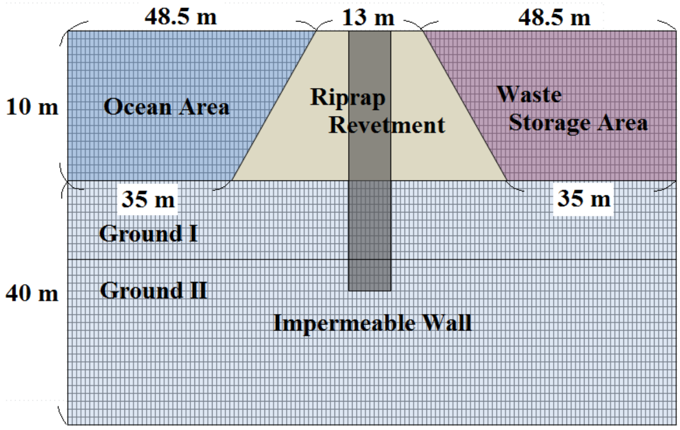


Figure 4. Schematic view of the analysis model

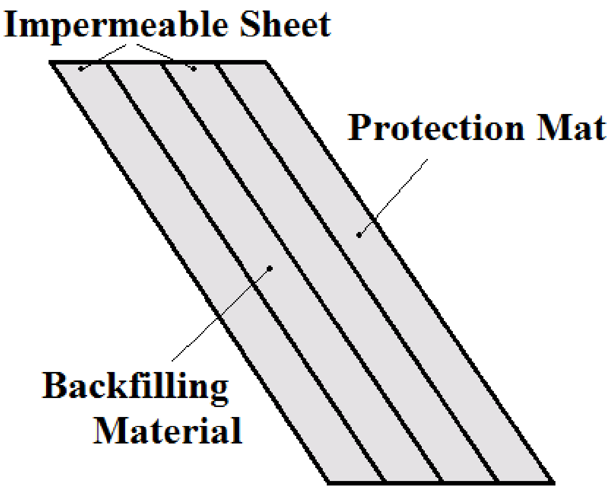


Figure 5. Schematic view of the impermeable layer

4.2. Boundary conditions

The boundary conditions of the analysis models are summarized in Table 3. The flow rate was set at zero at the bottom, right and left side of the analysis models and the top edge of the impermeable wall. Total hydraulic head was set at 10 m at the top edge of the ocean area and at 11 m at the top edge of the waste storage area as a fixed boundary: the difference in hydraulic head was set at 1 m. The concentration of contaminants was fixed at 1 in each location of the waste storage area.

4.3. Evaluation method

Some of the regulations in the environmental standard and the acceptable concentration of contaminants in ocean disposal sites are listed in Table 4. The environmental standard referred to the regulation enacted by the Ministry of the Environment in Japan [4], and the acceptable concentration referred to the Ordinance of Prime Minister's Office [5]. The concentrations in the environmental standard are one-tenth of the acceptable standard. Therefore, it was considered that the contaminants leaked from the disposal site when the relative concentration of the contaminants in the ocean area became one-tenth of the fixed concentration in the waste storage area in this study.

Table 3 – Boundary conditions

Elements	Environmental standard	Acceptable concentration
Hydrargyrum	< 0.01mg/L	< 0.1mg/L
Hexavalent chromium	< 0.05mg/L	< 0.5mg/L
1-3-Dichloropropene	< 0.002mg/L	< 0.02mg/L
Tetrachloroethylene	< 0.01mg/L	< 0.1mg/L

Table 4 – Environmental standard and acceptability standard for waste

Hydraulic head (m)	Top edge of ocean area	10
	Top edge of waste storage area	11
Fixed concentration (-)	Top edge of waste storage area	1
Flow rate (-)	Bottom, right and left side of the model, and top edge of the impermeable wall	0

5. Result and Discussion of Analysis for application of construction of ocean disposal sites

5.1. Comparison of the performance of an impermeable wall

The performance of an impermeable wall constructed using the CCC method were compared to that constructed using the conventional method in an ocean disposal site. Figure 4 shows the concentration of contaminants after 50 years in the analysis models. The area with red color indicates higher concentration of contaminants. The contaminants spread across a wide area in the disposal site constructed using the conventional method in Figure 4(a), in comparison with that by the CCC method in Figure 6(b). More than 0.1 of the concentration of contaminants was observed in the ocean area in Figure 6(a). On the other hand, the leakage of contaminants was not observed in the ocean area after 50years in Figure 6(b). Compared to the result in the disposal site constructed using the CCC method in Figure 6(b), the contaminants, additionally, spread widely along the impermeable wall under the waste storage area in the site constructed using the conventional method in Figure 6(a). Thus, the difference in the structure of the impermeable wall in the disposal site constructed using the conventional method and the CCC method affected the performance of the impermeable wall for the prevention of the leakage of contaminants from the waste storage area. It can be said that the impermeable wall constructed using the CCC method is appropriate for the prevention of the leakage of contaminants based on the results.

Considering the spread of pollutants along the impermeable wall in Figures 6(a) and (b), the water flow near the wall has to be discussed to understand the transfer of pollutants. Figures 7(a) and (b) show the total hydraulic head in the analysis models, and Figure 7(c) illustrates the enlarged view of total hydraulic head near the impermeable layer in the site constructed using the conventional method. The equipotential lines between the points of same hydraulic head are, moreover, drawn in Figure 7. Since the lines represent the difference in hydraulic head, the large distance between the lines indicates that hydraulic gradient becomes smaller with the decrease in water flow. Meanwhile, hydraulic gradient becomes larger with the increase in water flow when the distance of the line is small [6]. In Figure 7(a), the distance of the lines is, especially, small near the impermeable wall, indicating that the flow rate is high with the increase in hydraulic gradient along the wall. Additionally, the distance of the lines became small near the impermeable layer along the slope of the revetment in the site constructed by the conventional method as shown in Figure 7(c). This area corresponded to the boundary of the waste storage area and the revetment in Figure 7(a), where the concentration gradient is high since the difference in the concentration of pollutants is maximum between the areas. According to the Fick's laws of diffusion, the diffusive flux is proportionate to the concentration gradient [7]. Therefore, the spread of pollutions was accelerated by diffusion and advection due to the high hydraulic gradient and concentration gradient along the slope of the revetment in the site constructed using the conventional method. In the disposal site constructed using the CCC method in Figure 7(b), hydraulic gradient was high along the impermeable wall, while the concentration gradient was high at the boundary of the waste storage area and the revetment. Hence, the contaminants spread across a wide area in the site constructed using the conventional method due to the confluence of the areas along the slope of the revetment, where the concentration gradient and the hydraulic gradient were high. In the area under the disposal storage area, the distance of the equipotential lines is small near the impermeable wall in the site constructed using the conventional method compared to that constructed using the CCC method in Figures 7(a) and (b). It also caused an increase in flow rate near the impermeable wall owing to the increase of hydraulic gradient, resulting in the spread of pollutants in a wide area in Figure 7(a).

5.2. Effect of the location of an impermeable wall on the spread of pollutants

Considering that the difference in the structure of an impermeable wall affected the spread of pollutants as discussed in the previous section, the distance between an impermeable layer and the waste storage area may also affect the spread. For that reason, the effect of the distance of an impermeable wall and the waste storage area on the spread of pollutants was discussed in the three models as shown in Figure 6: an impermeable wall was set at ocean side of the revetment in Figure 8(a), it was set at the center of the revetment in Figure 8(b), and it was set at the waste storage area side of the revetment in Figure 8(c). The location of the impermeable wall differed by 5 m in each model. In this case, the permeability of the impermeable wall was set at 1.0 x 10^{-6} cm/sec and that of the ground was set at 1.0 x 10^{-5} cm/sec in each location of the ground. The length of the embedded impermeable wall into the ground was set at 10 m from the bottom of the sea, and the thickness was set at 100 cm. The difference in total hydraulic head between the ocean area and the waste storage area was set at 1.0 m.

The time for the pollutants to reach the ocean area under each condition is summarized in Table 5. Figure 7 shows the total hydraulic head with the equipotential lines in each model. The time decreased with the reduction of the distance between the permeable wall and the waste storage area as shown in Table 5. The distance of the equipotential lines became, furthermore, smaller in the area under the waste storage area with the decrease of the distance in Figure 9. This indicated that hydraulic gradient and flow rate were high near the impermeable wall under the waste storage area when the impermeable wall was constructed near the waste storage area [6]. The increase in flow rate caused the leakage of pollutants from the waste storage area earlier when the impermeable wall was constructed near the waste storage area. Therefore, the impermeable wall should be constructed on the ocean side for the prevention of the spread of pollutants.

6. Construction of impermeable wall by CCC

In January 2010, the CCC was adopted to the public works of restoring Miike Harbor in Omuta City, Japan. As a part of the entire works, two settling ponds were constructed for receiving dredged materials and the CCC took part in constructing impermeable walls of those settling ponds for preventing the contaminated water from flowing out, and from disturbing the environment of the surrounding area. The specifications of the first walls were 0.75 m in thickness, 7 to 8 m in depth, a total 1,128 m long and the total area was 8,470 m^2. The requested hydraulic conductivity value of the wall was less than 1.0 x 10^{-6} cm/sec. For ensuring the impermeability of the wall, soil samples were taken at the site and mix design tests were conducted. The obtained values were less than 2.0 x 10^{-7} cm/sec which is five times less than the designated value1).

Based on the test, the mix design was decided as follows:

- Type of cement   Blast furnace cement
- Cement factor   150 kg/m^3 of soil in-situ
- Water/cement ratio   150%

The CCC started the wall works of the first settling pond on 23rd of January 2010 and finished spending 35 days. The core samples taken from the constructed wall showed good results as shown in Table 6.

The hydraulic conductivity of the constructed wall is much less than designated value that was obtained from the mix design test. The productivity of the CCC was 250 m^2 /day and the cost of wall production was more than 20% cheaper than those using the conventional method. Figure 10 shows the CCC working at the first site.

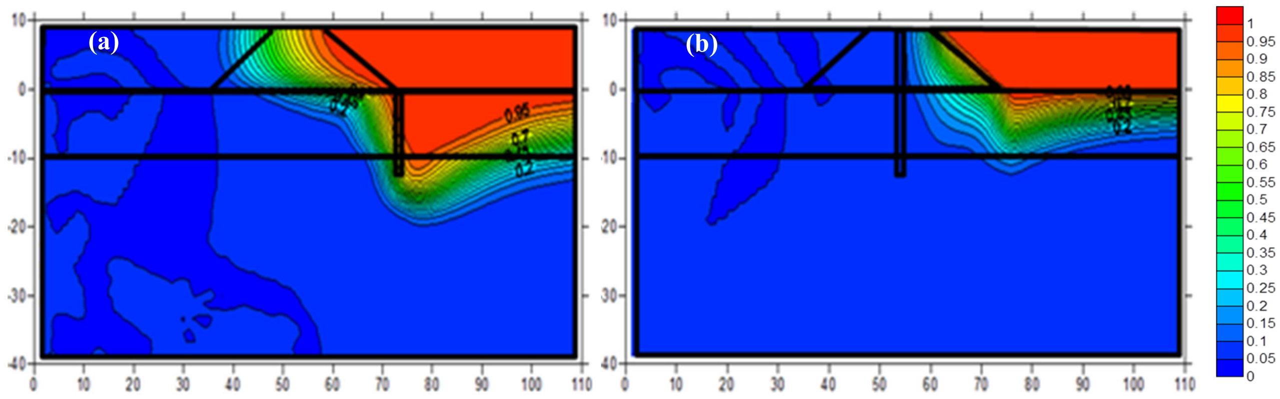


Figure 6. Concentration of contaminants after 50 years in the ocean disposal site: (a) constructed by the conventional method; (b) constructed by the CCC method

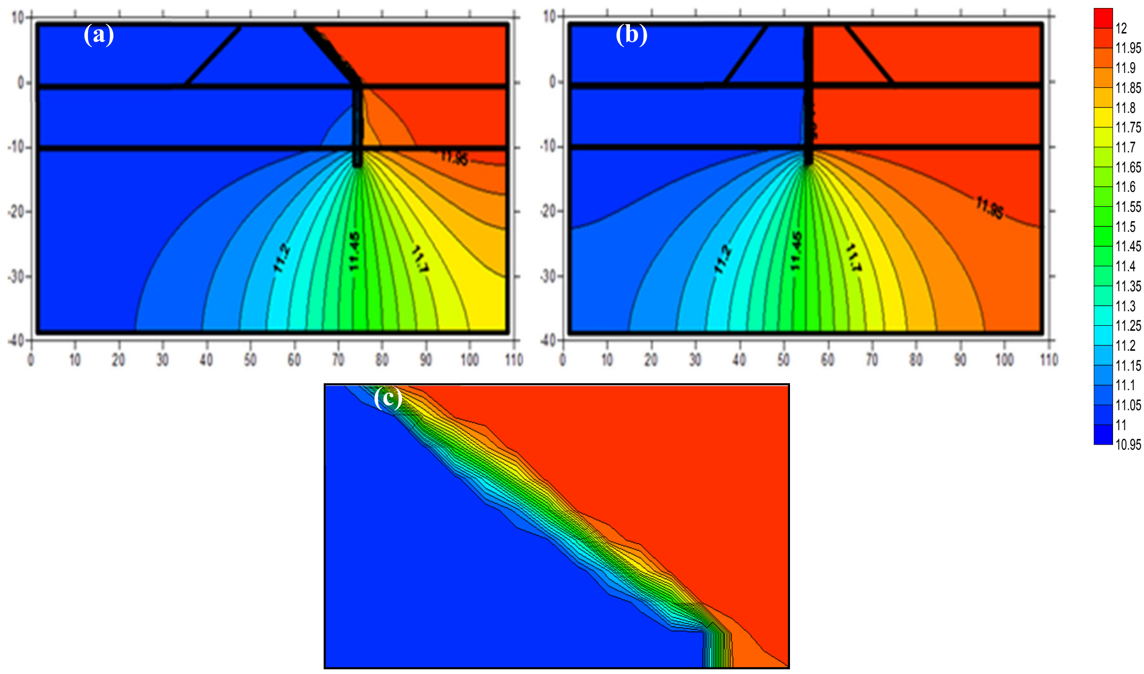


Figure 7. Total hydraulic head after 50 years in the ocean disposal site: (a) constructed by the conventional method; (b) constructed by the CCC method; (c) enlarged view along the impermeable layer in the site constructed by the conventional method

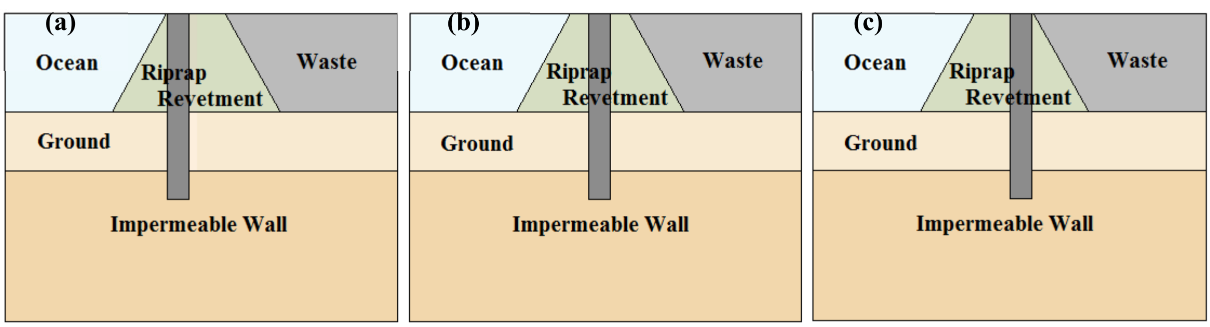


Figure 8. Analysis model with the impermeable wall: (a) at ocean side; (b) at central point; (c) at waste storage area side

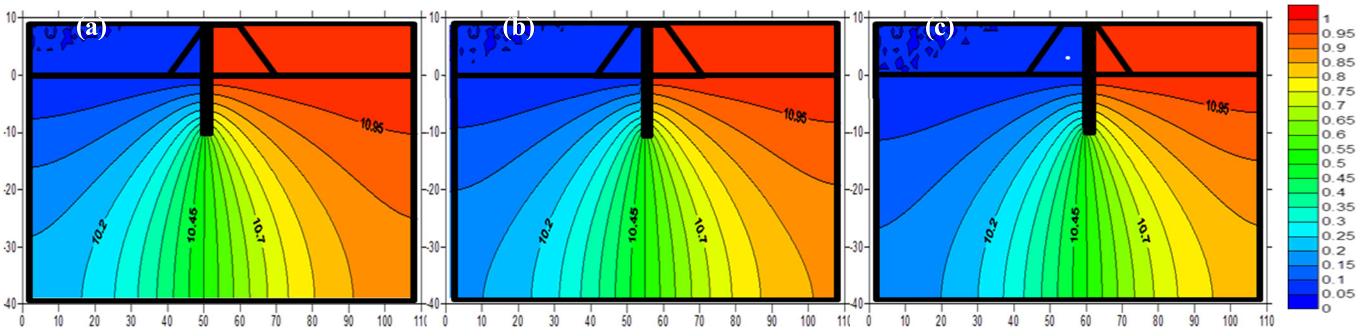


Figure 9. Total hydraulic head in each model with the impermeable wall: (a) at ocean side; (b) at central point; (c) at waste storage area side

Table 5 – Time when the pollutants reach to the ocean area

Location of impermeable wall	Ocean side	Center point	Waste storage area side
Time (year)	42	13	5

Table 6 – Hydraulic conductivity of the diaphragm wall

Bore Hole No.	Hydraulic Conductivity		
	Upper	Middle	Lower
1	4.83×10^{-8}	5.51×10^{-8}	1.70×10^{-7}
2	2.63×10^{-8}	4.11×10^{-8}	2.82×10^{-8}

Figure 10. Scenery of high power CCC

The second work started in April, 2010 and finished in July in Arao city located south of Omuta city, as shown in Figure 11. The specifications of the walls were 0.75 m in thickness, 8 to 10 m in depth, a total 1,197 m long and the total area was 10,420 m^2. The requested hydraulic conductivity value of the wall was same as the first wall of less than 1.0×10^{-6} cm/sec. According to the mix design test, the cement factor and the water/cement ratio were changed from 150 to 200 kg/m^3 of soil in situ and from 150 to 100%, respectively. This was due to the occurrence of thick layers of sand and gravel which easily pass the water and makes it difficult to establish an impermeable wall.

The actual performance of the CCC had interference caused by the hard rock filled in the ground and hard soils that were encountered. The N value of the hard ground was more than 50. In spite of the adverse conditions, the CCC finished the second work as scheduled and the samples taken from the constructed wall satisfied the target value of 2.0×10^{-7} cm/sec.

Figure 11. Diaphragm wall surrounding 2nd pond

7. Conclusions

Since the beginning of the development works of the CCC in 2002, the CCC demonstrated the advantage of its chain saw type mechanism in the field of constructing soil/cement mixed walls. The advantages of the CCC method include not only cost and the days spent for completing given works, but also the uniformity and quality of the constructed structure which is impossible for the existing auger type machines.

Moreover, the spread of pollutants from ocean disposal sites was simulated with Dtransu-2D, aiming at comparing the performance of the impermeable wall constructed using the CCC method and the conventional method. The result indicated that the leakage and the spread of pollutants were prevented in the disposal site where the impermeable wall was constructed using the CCC method compared to the wall constructed using the conventional method. Moreover, the pollutants reached to the ocean area earlier with the decrease in the distance between the impermeable wall and the waste storage area due to the effect of the high flow rate near the impermeable wall. Therefore, the CCC method can be applied to the construction of an impermeable wall in ocean disposal sites. The distance between the impermeable wall and the waste storage area in ocean disposal sites should be larger in order to minimize the effect of water flow near the impermeable wall on the spread of pollutants from the waste storage area.

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