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STUDY ON IMPERMEABLE CONSTRUCTION METHODS USING BENTONITE MIXED SOIL IN RESERVOIRS

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ABSTRACT: The use of bentonite is one of the solutions to compensate for the lack of clay used in the impermeable layer of reservoirs. We conducted mixing tests of bentonite-mixed soil and confirmed that the addition of bentonite to the base soil improved the imperviousness. Moreover, it was confirmed that the imperviousness of the bentonite-mixed soil was correlated with the swelling power of the bentonite, the amount of bentonite added, and the density. A reservoir was constructed using a bentonite mixture soil of the determined mix as the impermeable layer. The “vertical impervious wall method” and the “thin layer step cut method” were used for the impermeable construction method installed in the embankment. Observation wells were installed downstream of each embankment, and water levels were measured continuously after construction. The infiltration lines for each impermeable construction methods were predicted from the water level data. It was confirmed that the position of infiltration line was sufficiently lowered by the impermeable layer using bentonite-mixed soil in both methods.

Keywords: Bentonite mixed soil, Water blocking method, Embankment repair, The infiltration lines

1. INTRODUCTION

In 2017, Japan's Ministry of Agriculture, Forestry, and Fisheries (MAFF) released a report on the implementation status of detailed surveys, etc., based on a simultaneous inspection of reservoirs. Of the 4,444 reservoirs surveyed, 2,434, or 55%, were found to be inadequately earthquake-proof. It was also found that 1,399 reservoirs, or 38% of the 3,634 reservoirs surveyed, require heavy rainfall protection. As of May 2023, the number of reservoirs in Japan is expected to increase to 1,634, or 38% of the total number of reservoirs surveyed. As of May 2023, the number of priority agricultural reservoirs for disaster prevention in Japan is 53,399. Under these circumstances, the "Act on Special Measures Concerning Promotion of Disaster Prevention Work on Priority Agricultural Reservoirs for Disaster Prevention" was enacted in October 2020. The purpose of this law is to promote disaster prevention work on priority agricultural reservoirs in an intensive and systematic manner. Prior to 1989, dams in Japan were generally grouted to prevent water leakage. The stability of these dams has been identified as a problem with the stability of the levees when subjected to seismic motion, which is an extremely dangerous potential issue [1]. The sloping core zone method (Fig. 1) is commonly used for embankment retrofitting of reservoirs in Japan, in which impervious clay is placed upstream of the embankment to prevent leakage and improve the stability of the embankment by lowering the infiltration line position. In recent years, however, there have been some areas where rehabilitation has been delayed due to difficulties in securing clay around the reservoirs[2]. Securing impervious materials is an issue that must be resolved in order to renovate reservoirs. On the other hand, in Southeast Asian countries, efforts to ensure agricultural resilience by securing auxiliary water sources through the construction of small reservoirs, rather than large-scale water resource development, as a countermeasure against drought, have begun. However, some countries face challenges in securing water resources for agriculture due to the underdevelopment of water interception technology for reservoir construction. In this study, as an alternative impervious material to clay, we investigated the formulation of bentonite-mixed soil to ensure its performance as an impervious layer in reservoirs. We report on the construction of a reservoir with a new impervious layer using bentonite-mixed soil, and the reduction in infiltration was confirmed.

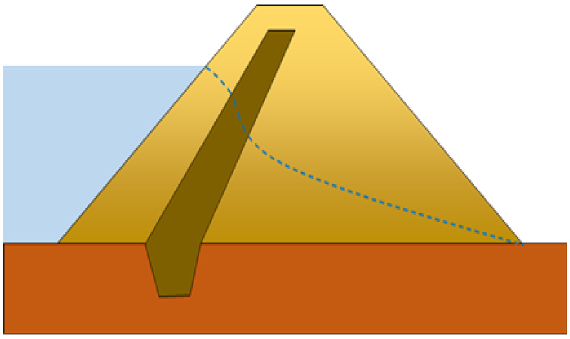

Fig. 1 Diagram of the sloping core zone method

2. RESEARCH SIGNIFICANCE

Artificial production of clay will make it possible to provide high-quality impervious materials in areas where impervious materials are depleted. An impervious layer of the same soil material as the levee body is expected to eliminate the strength gap that occurs inside the levee body and prevent the levee body from breaking due to earthquakes. The development of a simple impervious layer will help the construction of reservoirs in areas where impervious technology is not yet developed. This research can contribute to the stable supply of water for agricultural use and the creation of a safe rural environment.

3. MIXING TEST OF BENTONITE MIXED SOIL

3.1 Performance Requirements for Bentonite Mixed Soil

Bentonite mixed soil is a material obtained by adding a certain amount of bentonite to the base sandy soil and mixing it. The addition of bentonite makes it possible to improve the imperviousness of the base soil. There are several examples of application of bentonite-mixed soil to reservoir embankments in Japan, where bentonite-mixed soil was used as a substitute for clay used in the sloping core zone method. The performance required for impervious construction of reservoirs in Japan is a hydraulic conductivity k≤1.0 to 5.0x10-7m/s. In this study, the required performance of bentonite-mixed soil is k≤1.0x10-8m/s, which is a higher level than that of conventional clay. This is because the new construction method aims to make the impervious layer thinner, so the required performance was set to be 10 times higher than that of the conventional impervious layer.

3.2 Experimental Materials

Three types of Kagawa-produced decomposed granite soil were used as the base soil in the mixing test. Two types of bentonites, high swelling type and medium swelling type, were used. Table 1 shows the specifications of the base soil and bentonite used in this study. The properties of base soil and bentonite were investigated by laboratory tests. Table 2 shows the test results for each base soil and Fig. 2 shows the grain size additive curves. The physical property test results for bentonite are shown in Table-3. All of the base soils were slightly outside the range of applicable grain sizes for the impervious zone as indicated in the reservoir maintenance guidelines[3].

Table 1 Specification of base soil and bentonite

Item	Name	producing area	type
Based Soil	Soil-A Soil-B Soil-C	Kagawa, Japan	decomposed granite soil
Bentonite	BT-EF	Liaoning, China	Na Exchange, high swelling
	BT-AK	Gumma, Japan	Na Exchange, Middle swelling

Table 2 Results of physical tests of base soil

Items	Specification	Soil-A	Soil-B	Soil-C
Density of Soil Particles(g/cm^3)	JIS A 1202	2.627	2.667	2.640
Maximum particle size(㎜)	JIS A 1204	9.5	19.0	9.5
Fine fraction content(%)	JIS A 1204	22.7	12.6	23.3
Natural water content(%)	JIS A 1203	10.1	5.2	8.1
Oputimal water content(%)	JIS A 1203	14.6	12.3	17.2
Maxmum dry density(g/cm^3)	JIS A 1210	1.831	1.878	1.726

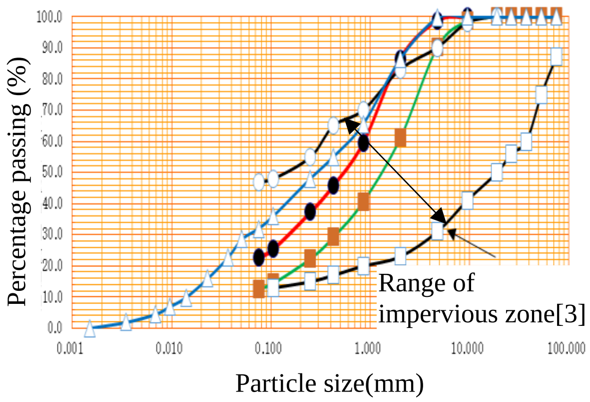

Fig. 2 Grain Size Accumulation Curve of Base Soils

Table 3 Physical Property Test Results for Bentonite

Item	Specification	BT-EF	BT-AK
Swelling power	JBAS-104-77	27.5	13.5
Bulk Density	JBAS-102-77	0.66	0.66
Moisture ontent	JBAS-101-77	8.6	5.6
pH	JBAS-105-77	10.4	10.5

3.3 Material selection of bentonite mixed soil

The use of bentonite mixed soil as an impervious material requires extra costs for bentonite material and production of bentonite mixed soil compared to conventional reservoir retrofitting methods. In addition, a high-precision mixing machine is required to mix a small amount of additive material homogeneously. In this study, assuming workability and cost in actual construction work, we aimed to secure the prescribed imperviousness with a bentonite addition rate of about 10%. The target addition rate was based on examples of bentonite mixed soil used in bottom liners of waste disposal sites in Japan. The specimens were prepared by compacting bentonite-mixed soil after mixing bentonite with the base material at the prescribed addition rate. The compaction nativity of the specimens was tentatively set at 90% of the maximum dry density of the base material. The target hydraulic conductivity and degree of compaction were also set with reference to the specifications of the impervious liner of the waste disposal site[4]. The required performance was set to k≤1x10-9m/s, which is one order of magnitude lower than the specification required in this study, to account for unexpected losses in the field. Fig. 3 shows a schematic diagram of the permeability tester.

Water was flowed through the bottom of the specimen and the amount of water and time were measured. The hydraulic conductivity(Kt) was determined by the following equation.

$$k_T = 2.303\frac{aL}{A(t_2-t_1)}\log\frac{h1}{h2} \quad / \quad 100 \qquad (1)$$

Where,
a: Cross-sectional area of standpipe (cm2)
(t2-t1): Measurement time (s)
h1: Water level difference at time t1 (cm)
h2: Water level difference at time t2 (cm)

After confirming that the time (t2-t1) passing through h1 and h2 is almost constant, perform the measurement at least three times. Fig. 4 shows the results of permeability tests of bentonite mixtures with 10% BT-AK added to three different base soils.

It was observed that the addition of bentonite improved the imperviousness of all base soils. In the BT-AK mixture with the same amount of bentonite, the bentonite mixture with substrate soil C, which contains more fine grains, showed the highest imperviousness. However, the target impermeability could not be achieved in the laboratory test.

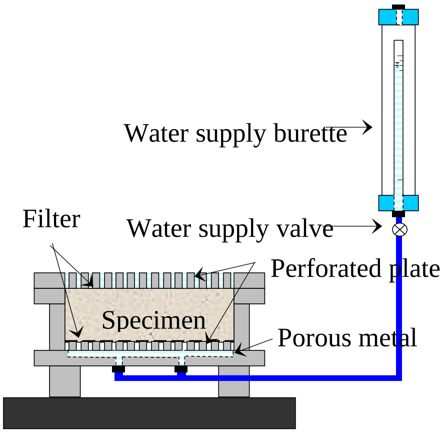

Fig. 3 Diagram of the Permeability Tester

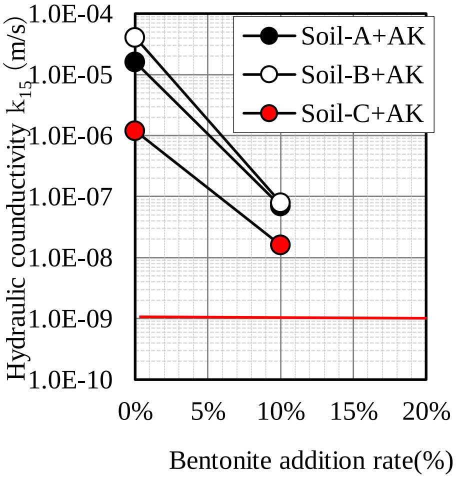

Fig. 4 Permeability of 10% AK bentonite mixed soil in each base material

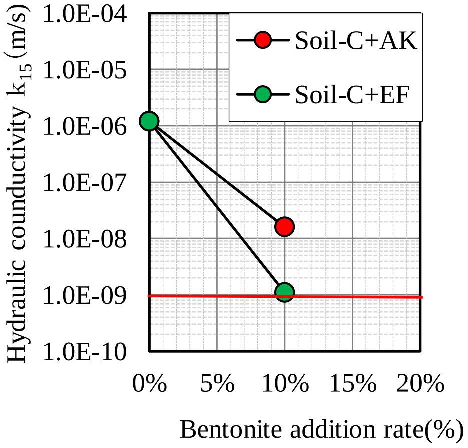

Fig. 5 Permeability test results of bentonite mixtures with the same amount of different bentonite added to base soil C

Fig. 5 shows the permeability test results of bentonite mixtures with the same amount of different bentonite added to base soil- C. For the same amount of bentonite mixture, the bentonite mixture with BT-EF, which has higher swelling capacity, exhibited higher imperviousness. Based on these results, it was decided to use base soil C and BT-EF in this study.

3.4 Determination of bentonite mixed soil

The physical properties of bentonite mixtures with different addition rates using Base Soil C and BT-EF were investigated. Laboratory permeability tests were conducted to determine the mix that would meet the required specifications at 90% and 95% compaction of the bentonite-mixed soil obtained from the test results. Table 4 shows the physical test results for the bentonite-mixed soil at each addition rate, and Fig. 6 shows the permeability test results for the bentonite-mixed soil at each degree of compaction. Based on the test results shown in Figure 6, the addition rate of the bentonite mixture used in this study was determined to be 13 % at 90 % degree of compaction and 10 % at 95 % degree of compaction.

4. PREDICTION OF INFILTRATION LINE OF BENTONITE MIXED SOIL IMPERVIOUS LAYER IN A FULL SCALE MODEL RESERVOIR

We constructed a full-scale model reservoir using the bentonite soil mixture we determined[5]. Of the four side embankments shown in the schematic (a) plan shown in Fig. 7, the south and north embankments had a bentonite-mixed soil impervious layer installed using the thin layer step cut method[6].

The east and west embankments were constructed using the vertical impervious wall method[7]. Fig. 7(b) shows a cross-section of the thin layer step-cut method, and (c) shows a cross-section of the vertical impervious wall method. After construction of a full-scale model reservoir, water levels were measured at a water-level observation well located downstream of the impervious layers. Water levels were measured using a rope-type water level gauge to confirm the interception effect of each interception layer and to predict the infiltration line in the actual site. (Fig. 8) Since the full-scale model pond is a dug-in reservoir, the water level in the observation wells was expected to be affected by rainfall and backwater. Water levels were measured eight times over a four month period after flooding. Observation wells 4-6 and 7-9, shown in Fig. 7 a), have the highest water levels downstream, indicating that they are heavily influenced by backwater from adjacent offsite buildings and drains.

Therefore, the seepage lines were predicted from the water levels in the observation wells except for observation wells 4-6 and 7-9.

Table 4 Physical test results for the bentonite-mixed soil at each addition rate

Item	Addition rate			
	4%	7%	10%	13%
Density of Soil Particles(g/cm^3)	2.640	2.655	2.665	2.666
Max. particle size(mm)	9.5	9.5	9.5	9.5
Fine fraction content(%)	25.6	28.2	29.2	31.6
Oputimal water content(%)	13.8	13.9	14.1	14.9
Max. dry density(g/cm^3)	1.842	1.830	1.812	1.784

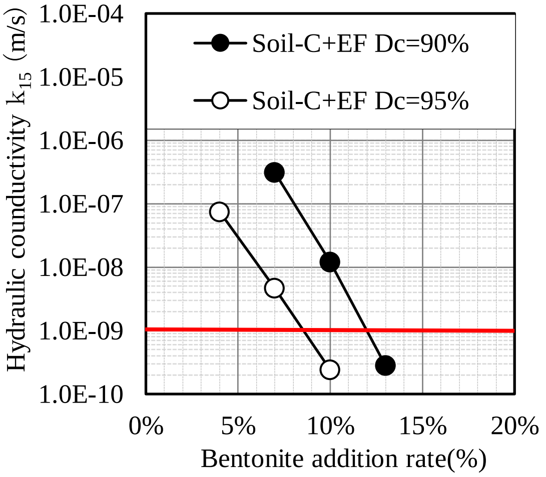

Fig. 6 Permeability test results for the bentonite-mixed soil at each degree of compaction

Table 5 shows the measured observation well water levels, and Fig. 9 shows the location of the infiltration lines through each barrier layer predicted from the observation well water levels. It was confirmed that the infiltration line in the embankment is located in the lower part of the embankment in all cases of the impervious construction methods.

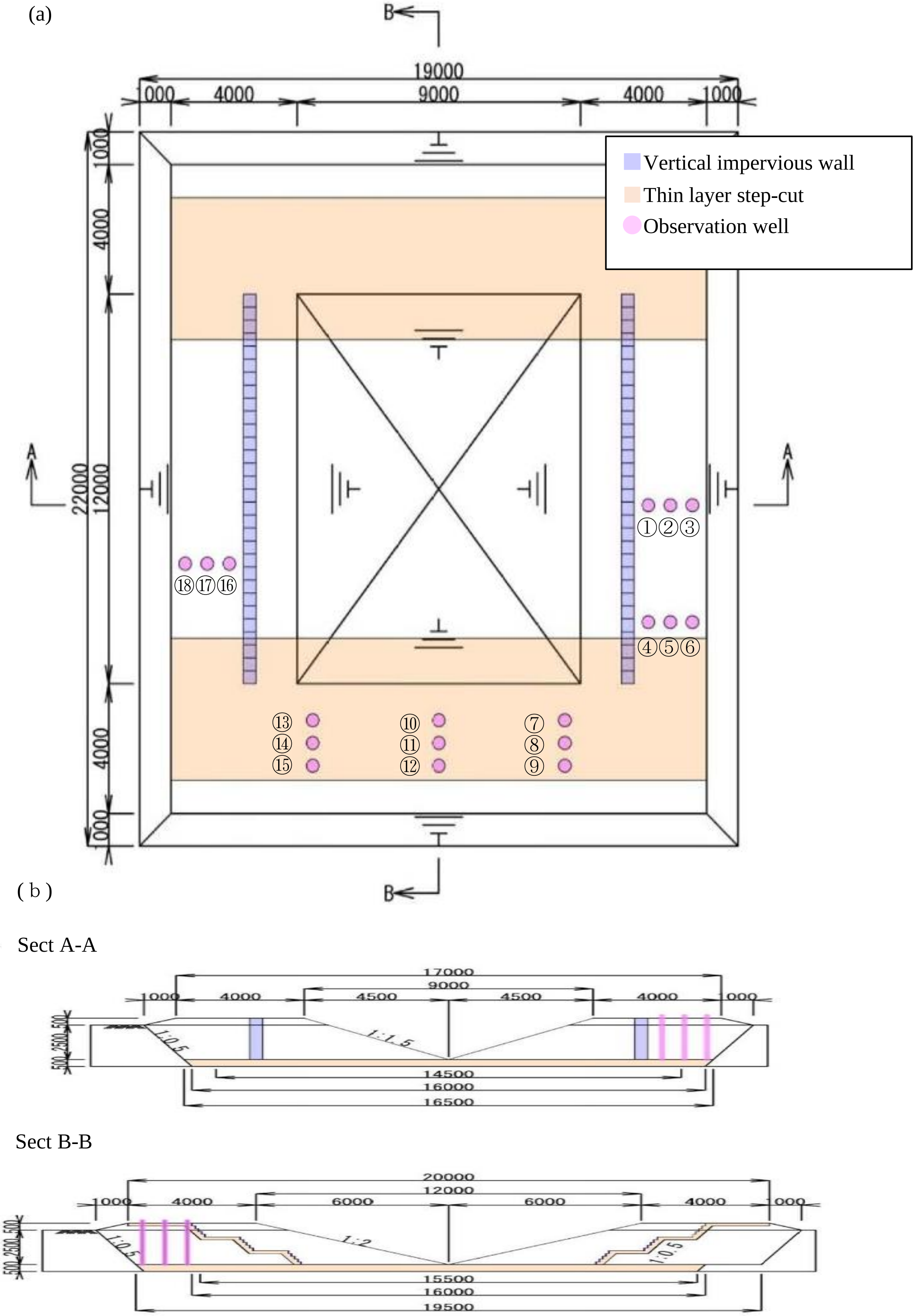

Fig. 7 Schematic diagram of a full-scale model reservoir (a) Plan view, (b) Cross-sectional view of thin layer step cut method, and(c) Cross-sectional view of vertical impervious wall method

Fig. 8 Rope-type water level gauge

Table 5 Water level of observation well

Method	Water level （㎜）		
	Up stream	Center	Down-stream
Thin layer step-cut	135.0	128.1	37.5
Vertical impervious wall	635.6	152.5	0.0

5. SEEPAGE FLOW ANALYSIS BY SOFTWARE

Prediction of the infiltration line in the embankment is an important consideration in the design phase of reservoir rehabilitation. Therefore, it is necessary to establish a method to predict infiltration lines in the design stage of new impervious construction methods.

An analytical model of steady seepage flow in a sloped core reservoir embankment was optimized to auto-mesh and saturated seepage flow analysis was performed using 2-D seepage flow analysis software.

The parameters of each layer used in the analysis were the results of permeability tests on core samples taken during the construction of the full-scale model reservoir. (Fig. 10)

Fig. 10 Status of Lab permeability test

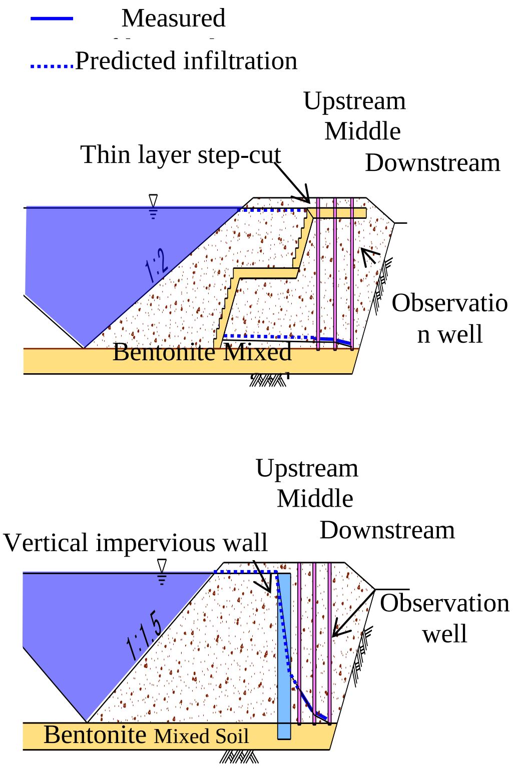

Fig. 9 Infiltration lines for each interception layer predicted from observed well water levels

Table 6 shows the permeability test results of the core samples.

Since the full-scale model pond is a dug-in reservoir and the soil cover is excavated soil, the soil cover and the downstream base were assumed to be identical, and the average hydraulic conductivity of the core samples in the soil cover layer was used as the parameter.

Table 6 Permeability test results

Point	Quantity	Average hydraulic conductivity
Bottom	2	$1.1\text{x}10^{-10}$m/s
Thin layer step-cut	6	$1.7\text{x}10^{-8}$m/s
Vertical impervious wall	9	$1.9\text{x}10\text{-}^{10}$m/s
Cover soil	12	$1.1\text{x}10^{-7}$m/s

Fig. 11 shows the predicted infiltration lines in the seepage flow analysis software. For all of the interception methods, the water level of seepage water that passed through the impermeable layer decreased, and its behavior was similar to the seepage line estimated from the observed water level in the observation wells of the full-scale model reservoir.

However, the seepage lines occurred at higher water levels than those measured by the full-scale model reservoir.

6. DISCUSSION

In the mixing tests, the imperviousness of bentonite-mixed soil was positively correlated with the swelling capacity of bentonite, the fine-grain content of the base soil, and the compaction density of the bentonite-mixed soil. These results suggest that the bentonite-mixed soil has a longer water permeability time due to the filling of voids by the water-absorbing swelling action of the bentonite.

The reason for the variation in water levels at the observation wells may be due to the influence of seepage water from outside the reservoir, since the reservoir is a full-scale model reservoir with a dug-in structure. In addition, the soil cover above the impervious layer and the non-uniformity of the soil texture in the downstream area were also considered.

The infiltration line prediction of the thin layer step-cut method shows that the infiltration water moved upstream. This indicates that the impervious layer may still be in the process of saturation.

The results of the two-dimensional seepage flow analysis and the infiltration line of the full-scale model reservoir showed similar behavior, but there was a difference in the water level.

This is due to the assumption of the same and uniform imperviousness of the locally excavated soil used for the soil cover and the downstream construction base.

7. CONCLUSIONS

From the results of the mixing tests of bentonite-mixed soil, the following conclusions were drawn.

(1) The addition of bentonite improves the imperviousness of the base soil.

(2) By adding bentonite to the decomposed granite soil produced in Kagawa Prefecture, it is possible to produce an artificial clay with imperviousness 10 times higher than that of clay used for the impervious layer of reservoirs.

(3) In the case of adding the same amount of bentonite, the imperviousness of the bentonite mixed soil was positively correlated with the swelling power of the bentonite.

(4) The fine-grain content of the base soil and the imperviousness of the bentonite mixed soil also showed a positive correlation.

(5) The same mix of bentonite was positively correlated with the density of the bentonite mixed soil.

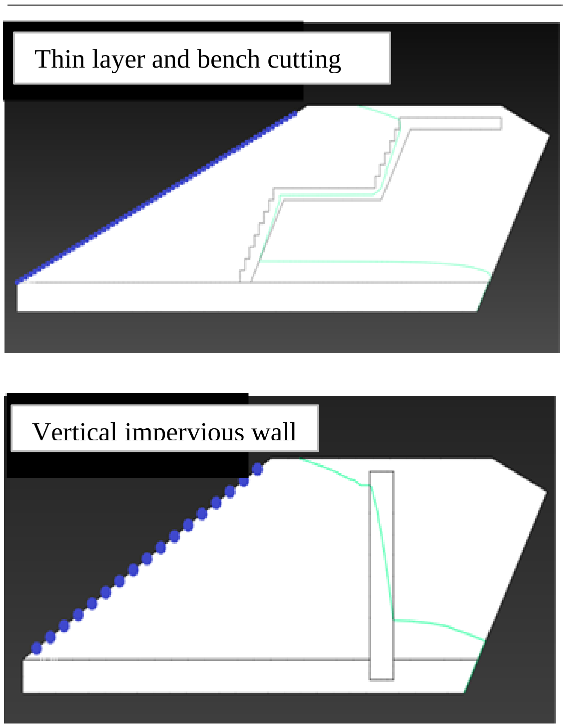

Fig.11 Infiltration lines predicted by seepage analysis

These results indicate that bentonite mixtures may be applicable to the reservoir levee impervious layer as a substitute for depletable clay.

Water levels measured at observation wells in a full-scale reservoir model indicated that seepage lines within the embankment were lowered through the impervious layer. The thin layer step cutting method and the vertical impervious wall method could lower the seepage line inside the levee in the same manner as the conventional sloped core method.

The infiltration lines predicted by the two-dimensional seepage flow analysis using software showed the same behavior as the infiltration lines assumed from the field observation wells, suggesting that the steady seepage flow analysis method for the inclined core type reservoir embankment may be applicable to the study of infiltration lines for the design of reservoir improvement using the new methods.

8. FUTURE CHALLENGES AND PROSPECTS

The results of this study do not clarify the behavior of the infiltration line upstream and downstream of the impervious layer. Furthermore, the state of saturation of the impervious layer is also unclear. We plan to continue measuring water levels in observation wells in a full-scale model reservoir and to evaluate the imperviousness of random materials upstream and downstream of the impervious layer.

Based on these results, the appropriate thickness and location of the impervious layer should be considered. It is also necessary to investigate the behavior of bentonite mixed soil in the embankment due to long-term inundation.

Bentonite is also used as a sealing material for artificial barrier systems in geological disposal of radioactive waste due to its physical and chemical properties, and is considered to have very little impact on the surrounding environment[8]. By confirming the impact on the environment when the reservoir is put into service, it is expected to be an effective water-proofing material not only in terms of water-proofing but also in terms of the long-term stability of the reservoir.

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