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Reinforcement effect of surface stabilizer using surface curtain walls on aging reservoirs

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Abstract. In Korea, accidents related to the collapse of deteriorated aging reservoirs occur every year. The grouting method is generally applied to reinforce an aging reservoir. However, when using this method, different reinforcing effects appear depending on the ground conditions. Thus, new construction methods and materials capable of providing consistent reinforcing effects are required. In this study, the direct shear test (DST), model test, and simulation analysis were performed to evaluate the impact of surface stabilizers, generally used to reinforce roads, rivers, and slopes of roads, applied using surface curtain walls on aging reservoirs. The DST results indicate that when the surface stabilizer was mixed with in-situ soil, the increase in cohesion was the highest at a mixing ratio of 9%. No changes in the friction angle were evident; therefore, 9% was determined to be the optimal mixing ratio. In addition, the model test and simulation analysis showed that when 9% of the surface stabilizer was mixed and applied to the aging reservoir, the seepage quantity of water and the saturated area were reduced by approximately 42% and 73%, respectively. Moreover, the comprehensive analysis of results showed that the grouting method could be completely replaced by surface stabilizers applied through surface curtain walls because the technique could secure stability by decreasing the seepage in the aging reservoir.

Keywords: aging reservoir reinforcement; reinforcement effect; simulation analysis; surface curtain walls; surface stabilizer

1. Introduction

Reservoirs have been built worldwide for flood control, water storage, and recreational activities (Juracek 2015). In particular, in Korea, numerous small reservoirs with a height of less than 10 m were built to supply agricultural water to farms mainly used for rice farming, which requires a lot of water (Hong 2004). However, 51.1% of the reservoirs were constructed before 1945, and 24.5% were constructed before 1970; thus, these reservoirs are over 75 and 50 years old, respectively (MAFRA 2018). Therefore, 75.6% of the reservoirs have exceeded the lifespan of 50 y stipulated in Korea, making aging a serious problem. In general, the usability and stability of a reservoir that is more than 50 years old decreases as the fine-grained soil inside it leaks over time. Moreover, a piping phenomenon occurs in which a new water path is formed inside the reservoir (Hajimirzaie and Hotchkiss 2020). Reservoirs aging because of these factors are at a high level of risk, and breakdowns can harm livestock and damage property (FEMA P-93 2004, Yang *et al.* 2011). Every year, accidents occur in aging reservoirs built in Korea owing to failures related to natural disasters, such as intensive rainfall and typhoons caused by abnormal weather, resulting in severe defects, such as water leakage and slope activity (Shin and Lee 2012, Choi *et al.* 2020).

As aging reservoirs continue to collapse, the institutions in Korea that manage reservoirs apply a grouting method to reinforce these reservoirs by filling the areas where water leaks or piping occurs (Song 2019). The grouting method is an economical method used to repair a reservoir. The technique involves the injection of an organic or an inorganic binder into the ground to fill the gap and upgrade its impermeability and mechanical properties (Toumbakari 2002). However, because the grouting method may exhibit different reinforcing effects depending on conditions such as injection pressure, strata, and groundwater, it is difficult to apply it consistently. Moreover, the direct verification of the part where the grout is completed is challenging (Song *et al.* 2017, Jinpeng *et al.* 2018). Ordinary Portland cement (OPC), which is commonly used as a grout material, presents the problem that 0.83 tons of carbon dioxide (CO_2) per ton of OPC are generated owing to the calcination of raw materials (e.g., limestone, clay, calcareous marl, and other clay-like materials) at a high temperature (approximately 1400℃) during the manufacturing process (Sanjuán *et al.* 2020). Consequently, the cement industry has been using materials such as gypsum, limestone, coal ash, or blast furnace slag as substitutes for OPC over the

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Table 1 Chemical constituents of surface stabilizer

	CaO	SiO_2	Al_2O_3	MgO	K_2O	Na_2O	TiO_2	Fe_2O_3	SO_3
Surface stabilizer (mg/kg)	26.23	37.06	19.67	12.42	0.18	1.22	1.38	0.58	None
OPC (mg/kg)	67.1	18.5	3.76	2.38	1.47	0.13	0.29	1.96	3.84

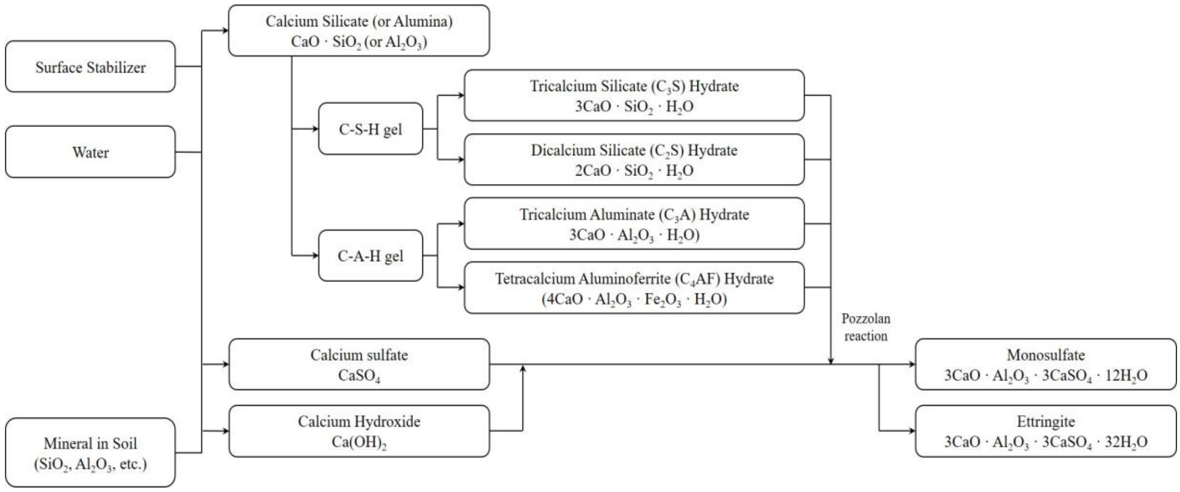


Fig. 1 Chemical curing reaction mechanism of surface stabilizer

past decade to reduce physical carbon dioxide emissions and environmental impacts (Durastanti and Moretti 2020). However, despite these efforts, CO_2 generated by OPC represents the third-largest anthropogenic source (approximately 8% of the total anthropogenic contribution). Moreover, the generated CO_2 has a severe impact on climate change (Andrew 2018). Owing to these environmental factors, the development of new materials and methods that can be applied to various ground conditions to solve environmental problems (including heavy metals and CO_2 generation) related to OPC are required (Kim *et al.* 2017, Kępniak 2019). Accordingly, several researchers have investigated the development of alternative materials to OPC using recycling resources, such as blast furnace slag, recycled glass fine powder, stone dust waste, waste gypsum, and oyster shells (Abdelkader *et al.* 2010, Islam *et al.* 2017, Kupwade-Patil *et al.* 2018, Tayeh *et al.* 2019, Dossena *et al.* 2019, Hu *et al.* 2019). However, in terms of construction methods, only the grouting method is applied widely. In particular, in Korea, even when an aging reservoir is reinforced, effective reinforcement is not achieved; moreover, geotechnical engineering problems are caused by the disturbance of the original ground, resulting in frequent collapse accidents (Park *et al.* 2017). In particular, the grouting method has a different reinforcement effect depending on several factors, such as injection pressure, rate and time of injection, and grout volume (Celik 2019). In addition, piping may occur when the permeability of groundwater is high, causing the injection material to flow out and pollute the environment. Thus, the development of new construction methods or improvement of existing ones is required.

Therefore, in this study, the reinforcement that is typically implemented for roads, rivers, and slopes of roads is proposed as an alternative to replace the grouting method. Specifically, the proposed approach involves applying a surface stabilizer with a coefficient of permeability (k) of less than 1.0×10^{-8} m/sec through surface curtain walls to the aging reservoir. To this end, after mixing the soil collected at the site and the surface stabilizer, laboratory tests were performed to derive the optimum mixing ratio, and the application method was determined through simulation analysis. In addition, a model test was performed for the case where the surface stabilizer was applied to the surface of the aging reservoir using the curtain wall method. The results were analyzed to determine whether the proposed approach could be applied to replace the grouting method.

2. Material

2.1 Surface stabilizer

In general, fly ash chemically reacts with calcium oxide (CaO) to induce the formation and hardening reaction of pozzolanic materials, and has the advantage of increasing the long-term strength of concrete, improving durability, and improving mechanical properties (Wang 2019). Thus, fly ash is used in various forms in the construction field. The main material of the surface stabilizer used in this study was fly ash. The chemical composition analysis results obtained through X-ray fluorescence (XRF) of the surface stabilizer are shown in Table 1. The XRF analysis indicates that the surface stabilizer has a relatively low content of CaO compared to OPC. However, as shown in Fig. 1,

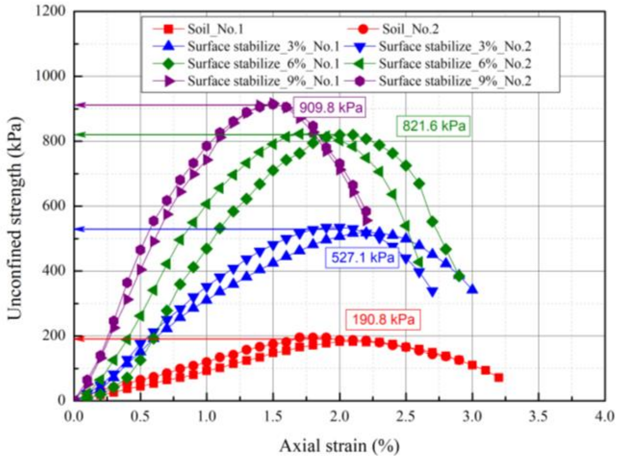


Fig. 2 Unconfined strength improvement by changing mixing ratio of surface stabilizer

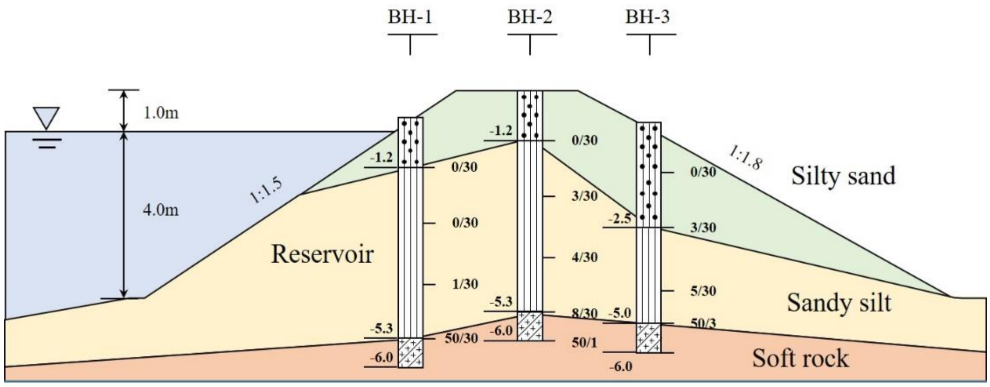


Fig. 3 Ground investigation results of aging reservoir

Table 2 Physical characteristics of in-situ soil

Water content (%)	Unit weight (kN/m^3)	Liquid limit (%)	Plastic index (%)	Percent finer (%)			USCS	Maximum dry unit weight (A method, kN/m^3)
				4.75 mm	2.00 mm	0.075 mm		
35.45	18.0	28.31	3.91	99.87	95.58	53.46	ML	17.94

calcium silicate hydrate (C-S-H), calcium aluminum hydrate (C-A-H), and ettringite can be produced, which can induce a curing reaction similar to that of OPC. In addition, when mixing with weathered granite soil of Korea, the compressive strength increases by approximately 2.76–4.77 times depending on the mixing ratio, as shown in Fig. 2. Moreover, it is possible to obtain a permeability coefficient of 1.0×10^{-8} m/sec or less (Bhang 2016).

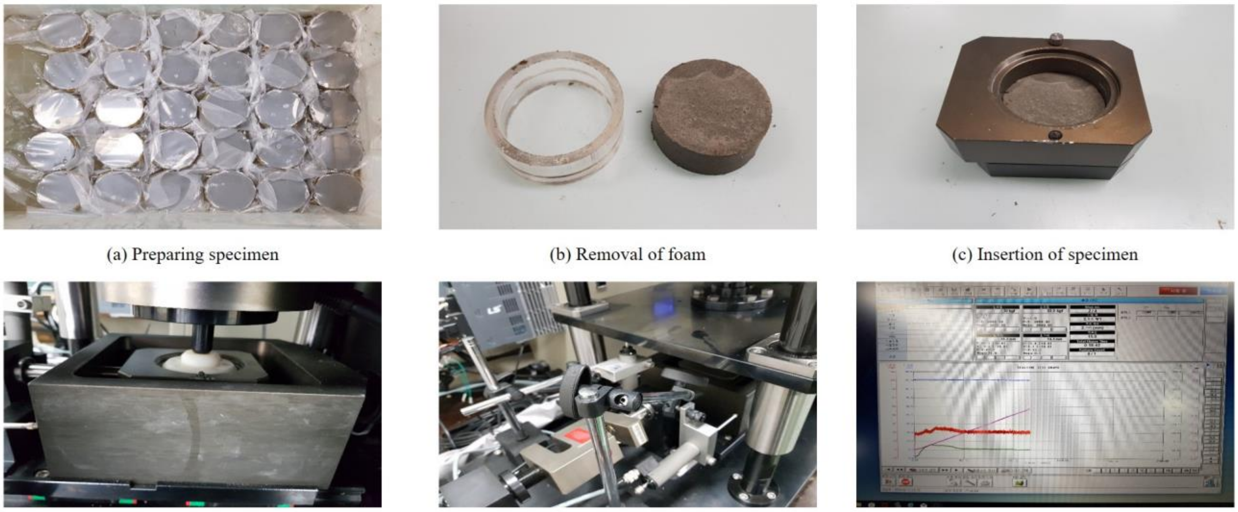
2.2 In-situ soil

In this study, the soil from an aging reservoir was collected to examine the reinforcement effect of applying the surface stabilizer to the aging reservoir using the surface curtain wall method. The soil was collected from a reservoir built before 1945; thus, the reservoir is now approximately 75 years old. The ground investigation results (Fig. 3) show that the *N* value of the standard penetration test is less than five, and the aging problem is serious. In this study, sandy silt was collected from the soil of the aging reservoir. Table 2 shows the physical characteristics obtained through laboratory tests performed on the collected soil.

3. Laboratory test to derive optimum mixing ratio

3.1 Design of test method

Laboratory tests were performed to determine the optimum mixing ratio for applying a surface stabilizer to the aging reservoir using a surface curtain wall. In this study, a direct shear test (DST) was performed among the unconfined compression and triaxial compression tests. In the DST, the cohesion (c) and friction angle (ø) were calculated, which represent the strength characteristics of soil material when analyzing the reinforcement effect of the aging reservoir. In addition, the DST can be conducted in a short time and is relatively simple. Thus, the derivation of the results is straightforward. The Korean test standard (KS F 2343 2017) was used to derive accurate results. Test equipment capable of loading vertical and horizontal loads up to 10 kN and 20 kN, respectively, was used to induce a reliable shear to the surface stabilizer, which has a higher compressive strength than general soil. In addition, a load



(a) Preparing specimen (b) Removal of foam (c) Insertion of specimen

(d) Installation in apparatus (e) Device setup (f) Measurement

Fig. 4 DST process

cell and displacement meter were installed to accurately measure the changes in normal stress, shear stress, and strain during the shear process. Fig. 4 shows the DST process using the test equipment.

3.2 Test condition

In general, the surface stabilizer is mixed with 6% of the weight of the soil to reinforce the slopes of rivers and roads (Bhang 2016). However, this study focused on deriving the optimum mixing ratio to ensure stability when a surface stabilizer is applied to an aging reservoir in the form of a surface curtain wall. In this regard, the mixing ratio was set to 6% and changed from 3% to 12% by increments of 3%. In general soil, the compressive and shear strengths vary according to the unit weight. Therefore, following the Korean standards (KS F 2312 2016; MLIT 2011), the Proctor compaction test (A method) was performed to derive consistent results for the site soil. Based on the results of this test, the dry unit weight and optimal water content ratio (ω_{opt}) corresponding to 90% compaction degree (D_C) were applied. In a surface stabilizer, a curing reaction similar to that of cement occurs over time. Therefore, in this study, specimens were prepared by mixing soil with optimum water content and a surface stabilizer, and then instantly compacting in a mold. Next, curing was performed for 1, 3, 7, 14, and 28 days. In addition, a DST was performed on each specimen to determine the change in adhesion (c) and friction angle (ø). Table 3 lists the test conditions used in the study.

3.3 Optimum mixing ratio through analysis of test result

The DST is a test method based on the Mohr–Coulomb theory to determine the change in shear strength (τ_f) as the vertical stress (σ_v) increases. In this method, the cohesion (c) and friction angle (ø) (Das and Sobhan 2013) are calculated.

Table 3 Test conditions used in this study

Water content (%)	Dry unit weight (kN/m^3)	Degree of compaction (%)	Mixing ratio (%)	Curing time (day)
14.54	16.15	90	3, 6, 9, 12	1, 3, 7, 14, 28

Table 4 Test results of DST

Content	Mixing ratio (%)	Curing time (day)					Remark
		1	3	7	14	28	
Cohesion (kPa)	3	216.7	236.5	264.3	269.3	266.6	52.5 kPa (in-situ soil)
	6	274.6	293.7	382.9	394.8	411.1	
	9	431.3	586.2	709.6	696.3	761.0	
	12	479.6	537.9	699.6	767.5	804.6	
Friction Angle (degree, °)	3	33.0	34.3	33.1	33.1	33.4	33.4 ° (in-situ soil)
	6	34.7	35.3	35.5	35.5	35.9	
	9	34.9	35.6	35.4	36.0	36.5	
	12	34.3	34.8	35.8	34.6	35.1	

In this study, to determine the relationship between the vertical stress and shear strength according to the mixing ratio of the surface stabilizer and the change in cohesion and friction angle through DST, the vertical stress was measured in four steps up to 100 kPa, 200 kPa, 400 kPa, and 800 kPa. Next, the shear strength of the specimen was used. Table 4 shows the DST results, and Figs. 5 and 6 show the changes in cohesion and friction angle according to the mixing ratio of the surface stabilizer measured through the DST.

Fig. 5 shows the change in cohesion (c) according to the mixing ratio of the surface stabilizer. The figure also shows that the cohesion increases as the curing time increases for all mixing ratios. However, after 7 days, the increase in cohesion is not significant, thus it can be ignored. As the mixing ratio increases, the cohesion increases up to a

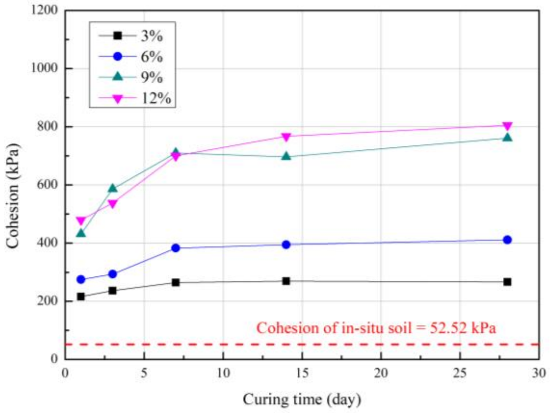


Fig. 5 Change in cohesion by varying mixing ratio of surface stabilizer

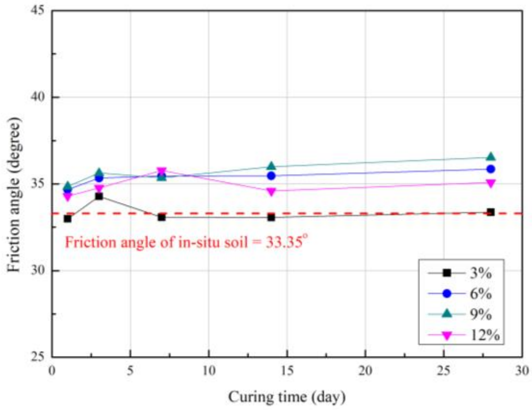


Fig. 6 Change in friction angle by varying mixing ratio of surface stabilizer

mixing ratio of 9%. However, at a mixing ratio of 12%, the cohesion is almost 9%. Fig. 6 shows the change in the friction angle (ø) according to the mixing ratio of the surface stabilizer. The value of friction angle remains almost the same value with changes in the mixing ratio and curing days, indicating that there was no significant change. According to the results of previous studies, when mixing with weathered granite soil in Korea, the compressive strength increases linearly up to a mixing ratio of 6%, and the compressive strength does not increase significantly when the mixing ratios exceed 6% (Bhang 2016). However, in this study, the DST results for cohesion showed that the mixing ratio was increased to 9%, and no change was found in the friction angle. When considering Mohr–Coulomb theory based on the test results, the shear strength of the surface stabilizer is maximum at a mixing ratio of 9%; therefore, a mixing ratio of 9% was determined as the optimal mixing ratio when applying a surface stabilizer to the aging reservoir.

4. Application method evaluation through simulation analysis

4.1 Analysis section

In the case of applying the surface stabilizer in the form of a surface curtain wall to the aging reservoir, simulation analysis was performed by changing the reinforcement location, depth, and length to determine the application method, ensuring the stability of the aging reservoir. When using the program to analyze stability, different results may be derived depending on the layer of soils, groundwater conditions, and slope. Therefore, in this study, the aging reservoir analysis section was simplified and implemented, as shown in Fig. 7, to easily evaluate the stability change due to the reinforcement of the surface stabilizer. As shown in the figure, the ground investigation was performed, and in-situ soil was collected. The surface stabilizer was considered to be applied to slopes, levees, and underground based on inland, which cause a decrease in the stability of the reservoir owing to penetration. As shown in Fig. 8, the surface stabilizer is applied to reinforce only the slope (case 1), the slope and levee (case 2), the slope and underground of inland (case 3), and the slope, levee, and underground of inland (case 4). In each section, the reinforcement depth at the slope, levee, and underground of inland increases by 1.0 m, from the minimum of 1.0 m to the maximum of 3.0 m, and the reinforcement length at the levee and underground of inland increases by 0.5 m, from the minimum of 1.0 m to the maximum of 2.0 m.

Table 5 Properties of the layer considered in simulation analysis

Layer	Unit weight (γ, kN/m^3)	Cohesion (c, kPa)	Friction angle (°)	Coef. of permeability (m/sec)
Reservoir	18.0	52.5	33.3	6.47×10^{-5}
Underground	18.0	52.5	33.3	6.47×10^{-5}
Surface stabilizer	19.5	700	35.9	8.77×10^{-5}

4.2 Analysis condition

The conditions of the soil layer (reservoir and underground) used for the analysis were obtained from laboratory tests on in-situ soil. The cohesion (c) and internal friction angle (ø) were obtained by conducting the DST on specimens where a compaction degree (D_C) of 90% was applied to a material mixed with 9% of the surface stabilizer (KS F 2343 2017). The coefficient of permeability (k), calculated by conducting a falling-head test for three specimens manufactured with a compaction degree (D_C) of 90% in a mold with a diameter (D) of 100 mm and a height (L) of 125 mm, was applied to the result (KS F 2322 2015). Among the models included in the analysis program, Geostudio 2012, the Mohr–Coulomb model was applied as the ground model because it is widely used to simulate most of the ground, and the van Genuchten model was considered as the hydraulic model (Geoslope 2020). Table 5 lists the properties of each layer used in the simulation analysis.

4.3 Result analysis

When designing a reservoir, the condition immediately after the construction of the reservoir, the condition at the

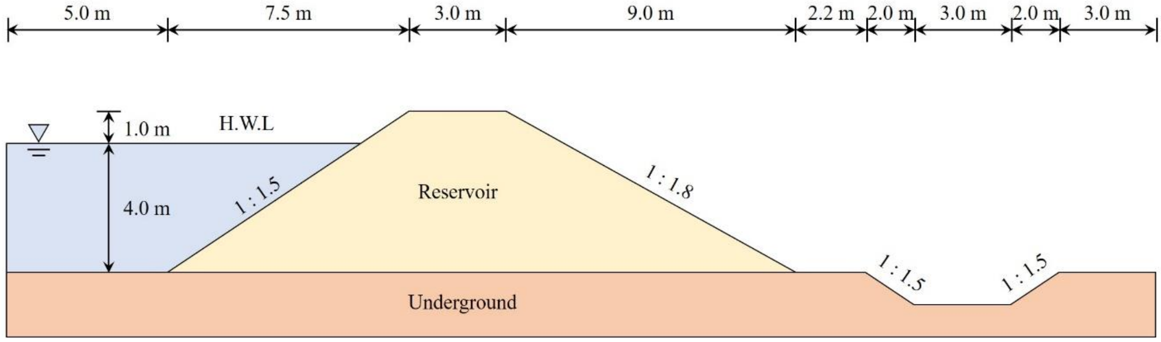


Fig. 7 Analysis section used in this study

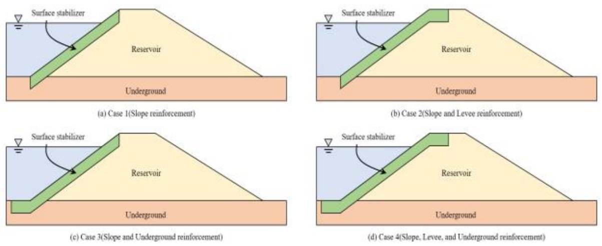


Fig. 8 Application method of surface stabilizer for aging reservoir

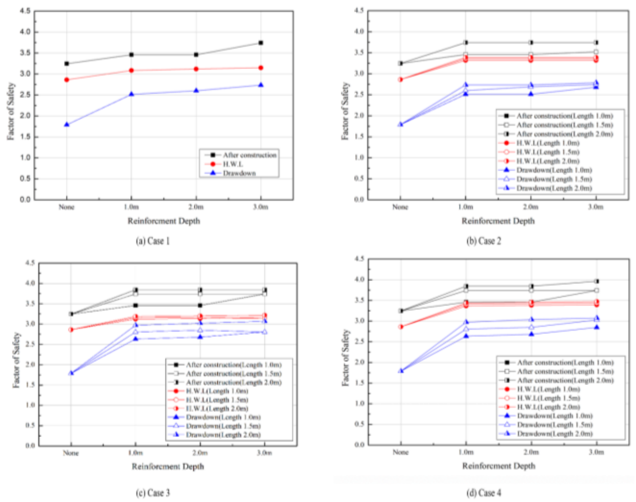


Fig. 9 Comparison of F_S in study cases

flood level, and the condition where the water level decreases rapidly due to the rapid drainage of the stored water for a short period are recognized as the conditions with the least stability (Hopkins *et al.* 1975). Therefore, in this study, simulation analysis was performed under the condition immediately after the construction of the reservoir (■), the condition at the flood level (●), and the condition in which the water level reduces rapidly (▲). Fig. 9 shows the factor of safety (F_S) according to the change in the reinforcement depth and reinforcement length by analyzing each section.

Fig. 9(a) shows the change in F_S according to the change in the reinforcement depth when only the slope is reinforced (case 1). In the figure, as the slope is reinforced, no significant change is found in F_S under the condition immediately after construction (■) and the condition at flood level (●). However, under the condition in which the water level reduces rapidly (▲) when the reinforcement depth of the slope is 1.0 m, F_S increases by approximately 1.4 times compared to the unreinforced case. Moreover, F_S does not increase significantly after that depth even when the reinforcement depth increases to 3 m. Therefore, only 1.0 m of reinforcement depth of the slope is sufficient.

Fig. 9(b) shows the change in F_S according to the change in reinforcement depth and length for case 2. In the figure, when the reinforcement depth at the slope and the levee increases, the overall F_S exhibits a similar increase to that when reinforcing only the slope. However, compared to F_S when reinforcing the embankment and the slope (case 1), a high F_S is observed under the condition of flood level (●). Moreover, compared to F_S when reinforcing the slope (case 1), F_S is 1.06–1.10 times higher under the condition of flood level (●). In addition, as the reinforcement length at the levee increases, F_S increases slightly and remains almost constant. Therefore, based on these results, reinforcing the levee is advantageous to secure the stability of the aging reservoir under the condition of the flood level.

Fig. 9(c) shows the change in F_S according to the change in the reinforcement depth and length when reinforcing the slope and underground inland (case 3). In the figure, F_S is higher under the condition immediately after construction (■) and under the condition in which the water level decreases rapidly (▲) than in the case where only the slope is reinforced (case 1). The value of F_S increases as the reinforcement depth and reinforcement length in the slope and underground inland increase. However, a small increase is found in F_S at the flood level (●). In addition, F_S is higher under the condition immediately after construction (■) and under the condition in which the water level decreases rapidly (▲) compared to that of case 2. However, F_S under the condition of the flood level (●) is low. Therefore, the reinforcement of the underground inland is advantageous when it is necessary to secure F_S under the condition immediately after construction and under the condition in which the water level decreases rapidly.

Fig. 9(d) shows the change in F_S according to the change in the reinforcement depth and length when reinforcing slopes, levees, and underground inland (case 4). In the figure, F_S is the highest in all cases when the slope, levee, and underground inland are all reinforced. Moreover, F_S increases consistently with increasing reinforcement depth and length.

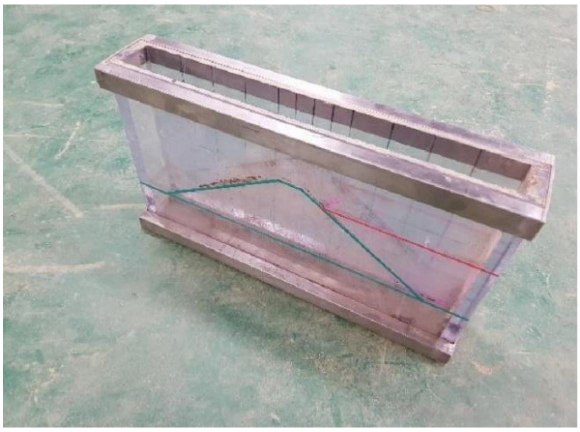


Fig. 10 Chamber used in model test

Fig. 11 Section of model test

In general, in aging reservoirs, it is known that numerous collapses occur because of the removal of fine particles for a long period, piping that forms waterways inside the reservoir, and overtopping during flooding due to natural disasters (Chen *et al.* 2019). Therefore, when the surface stabilizer is applied using the surface curtain wall method, the most effective method is to secure the stability of the condition at the flood level and the condition in which the water level decreases rapidly by reinforcing the slope, levee, and underground of inland (case 4). In the case of the reinforcement depth, F_S increases by approximately 1.4 times when the reinforcement depth is 1.0 m and does not increase significantly thereafter; thus, applying 1.0 m of surface stabilizer is considered adequate. In addition, F_S increases as the reinforcement length increases; thus, it is considered appropriate to apply the reinforcement length according to the particular condition of the aging reservoir.

5. Consideration of reinforcement effect through model test

5.1 Outline of model test

Model tests were performed to examine the reinforcement effect of applying a surface stabilizer on an aging reservoir. The model test dimensions were set as follows: length (L) 800 mm, width (W) 50 mm, and height (H) 250 mm. All test sides were made of transparent acrylic; thus, a chamber (Fig. 10) designed to check the change in the seepage area was used. The reinforcement of the surface stabilizer used a method of simultaneously reinforcing the slope, levee, and underground inland, which was derived to secure the highest F_S through the simulation analysis. In addition, the reinforcement depth and length of the surface stabilizer were 1.0 m and 2.0 m, respectively. However, when reinforcing the underground inland, the water that penetrated was insufficient owing to insufficient chamber length. Therefore, in the model test, the underground inland was not reinforced to induce smooth seepage. The material used consisted of in-situ soil collected from the aging reservoir and the surface stabilizer. Moreover, the unit weight used in the simulation analysis (18.0 kN/m^3 for soil, 19.5 kN/m^3 for surface stabilizer) was applied. For the model test section, 1/42 of the maximum scale applicable to the chamber was applied to the simulation analysis section (Fig. 11). The soil and surface stabilizers were prepared by calculating the required weight every 50 mm according to the scale, and then compacting.

5.2 Result of model test

In the model test, the water level of the reservoir was defined by calculating the scale based on the ordinary water level of the aging reservoir, 4.0 m. Moreover, the model test was performed for approximately 70 hour to ensure sufficient seepage occurred inside the aging reservoir, and to compare the reinforcing effect of the surface stabilizer. Fig. 12 shows the change in the seepage area with time for the unreinforced and reinforced aging reservoirs. The surface stabilizer was applied using surface curtain walls. Fig. 12(a) shows the change in the seepage area with time in the unreinforced aging reservoir. During the model test, a change in the seepage area was confirmed. Fig. 12(b) shows the change in the seepage area with time in the aging reservoir, reinforced in the form of surface curtain walls using a surface stabilizer. Leakage and capillary phenomena occur between the surface stabilizer and the chamber. Therefore, it is difficult to determine the change in the actual seepage area. In the reinforced model test, black ink was used to determine the change in the actual seepage area. Fig. 12(a) shows the change in the seepage area with time in the unreinforced aging reservoir. Seepage was performed parallel to the slope for 60 min. After the complete saturation of the underground inland, seepage occurred in the horizontal direction.

However, Fig. 12(b) shows the change in the seepage area with time in the reinforced aging reservoir, demonstrating that most of the seepage was from the unreinforced underground of inland. In addition, even after the underground inland saturation, most of the seepage occurred only on the underground of the inland, showing a difference from the unreinforced state.

A seepage analysis was performed under the same conditions as the model test using Geostudio 2012 (Geoslope 2020) to accurately compare the model test

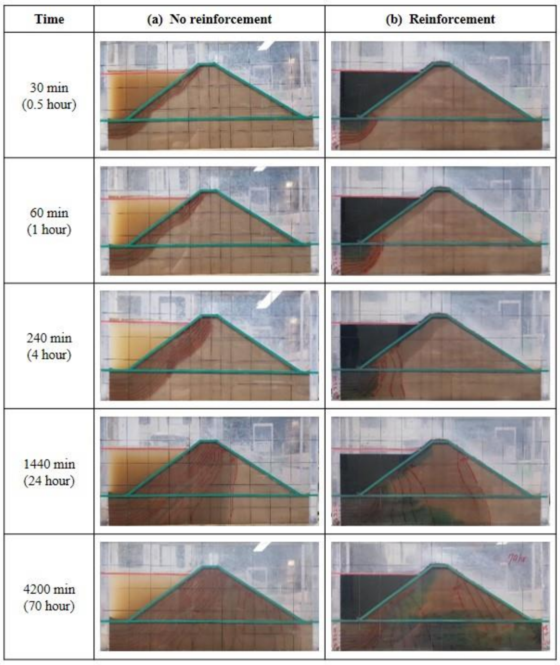


Fig. 12 Comparison between model test results

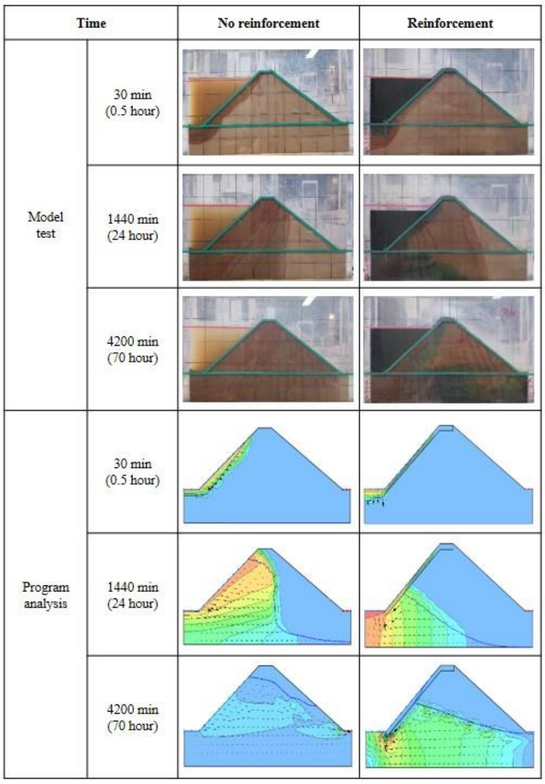


Fig. 13 Comparison between simulation analysis and model test results

results. The properties used in the seepage analysis were the same as those shown in Table 5, such as unit weight (γ), cohesion (c), friction angle (ø), and permeability coefficient (k), which were used to derive the application method of the surface stabilizer. Fig. 13 shows the comparison between the simulation and model test results. In the figure, the seepage into the aging reservoir with time shows a similar trend to that of the model test results. In addition, the seepage quantity of water calculated through simulation analysis was 1.0318 m^3/hour and 0.5996 m^3/hour for the unreinforced and reinforced aging reservoir, respectively. Moreover, the calculated ratio of the saturated area below the phreatic line to the total sectional area in the aging reservoir was found to be 81.3% and 22.1% for the unreinforced and reinforced aging reservoir, respectively. Based on these results, it can be concluded that when the aging reservoir is reinforced using a surface stabilizer, the seepage quantity of water can be reduced by approximately 42% and the saturated area by approximately 73%. In addition, when the seepage quantity of water and the saturation area decrease, the effective stress (σ') and shear strength (τ_f) increase. Thus, the proposed reinforcement can be used effectively to secure the stability of an aging reservoir against the collapse and deformation caused by natural disasters.

6. Conclusions

In this study, laboratory tests, model tests, and simulation were performed to evaluate the application of surface stabilizers used for the reinforcement of the slopes of rivers and roads as surface curtain walls of an aging reservoir. Based on the obtained results, the following conclusions can be drawn:

- The DST showed that the increase in cohesion (c) for mixing ratios of the surface stabilizer exceeding 9% was not significant. Moreover, the friction angle (ø) showed almost the same value; thus, 9% was determined to be the optimal mixing ratio of the surface stabilizer.
- As a method for aging reservoirs, the use of surface stabilizers through surface curtain walls to reinforce slopes, levees, and underground inland simultaneously showed the highest F_S. Moreover, it was found to be the most effective method for securing stability.
- The model test on the aging reservoir showed that most of the seepage area of water comprised the unreinforced underground when the surface stabilizer was used, and the seepage area significantly decreased compared to that of the unreinforced section.
- The simulation results of the model test indicated that when the surface stabilizer was applied by surface curtain walls, the seepage quantity of water and the saturated area could be reduced by approximately 42% and 73%, respectively.
- A comprehensive analysis of all tests and simulation analysis revealed that the stability of the aging reservoir could be secured by decreasing the overall penetration in the aging reservoir when the surface stabilizer was applied by surface curtain walls.
- Subsequently, if on-site verification is performed, the proposed approach can be used instead of the grouting method. Accordingly, the proposed approach can overcome environmental problems caused by cement as a grout material. Moreover, the method can decrease the collapse of aging reservoirs due to inadequate reinforcement by the grouting method.

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