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Permeation grouting for remediation of dam cores

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ABSTRACT

Grouting methods are known to effectively remediate the dam foundation or the abutment. However, remediation grouting of the deteriorated embankment earth-core itself has rarely been performed or studied. In this study, low-pressure permeation grouting is adopted to remediate the deteriorated central core layers of five aging dams. Technical features of each dam's deterioration are described, such as sinkholes, slope failures, fluidized clay cores, and wet zones on the downstream surface induced by excessive seepage. This study suggests several empirical standards for the application of permeation grouting to the improvement of core permeability, including grout mix, injection period per stage, injection rate, and maximum fluid pressure to prevent hydraulic fracturing. The results of this empirical case study can be applied to effectively remediate degraded dam embankment cores to decrease their permeability and minimize the risk of hydraulic fracturing, without requiring a reduction in the reservoir water level.

1. Introduction

Grouting methods have been widely applied to general ground improvement in the field of engineering geology (Warner, 2004). New dam constructions generally require pressure-type grouting of the foundation and associated abutments (Bruce, 2012). Existing dams built on alluvial deposits or permeable abutments are susceptible to excessive leakage and/or liquefaction induced by seismic activity (Ghobadi et al., 2005; Marcuson III et al., 1996). Therefore, foundation treatment cut-off systems or rock-mass grouting have been utilized frequently (Bruce et al., 2006; Turkmen, 2003; Unal et al., 2007; Uromeihy and Barzegari, 2007; Warner, 2004). Contemporary grouting applications include remedial grout curtains in rock under and around existing dams, jet grouting in soils underlying existing embankments, and interface-sealing between embankments and foundation rock, which is mostly accomplished by a pressure grouting technique (Stare et al., 2012a).

However, remediation grouting of the clayey earth-core layer of an embankment itself has rarely been performed in cases where there is a deficiency of seepage control induced by dam aging, incompleteness of compaction at the time of construction, inappropriate material selection, or seismic loading. To address problematic seepage from existing dams that maintain the current water supply, a grouting method can be applied to the deteriorated core layers without reducing the reservoir's water level. However, applying remediation grouting directly to the embankment is technically challenging.

For remediation grouting of dam core layers, the main purpose should be the improvement of core impermeability (Foster et al., 2000). Toward this objective, the delicate grouting procedure of grouting should be approached with care to achieve the contradictory technical goals of maximizing the filling of voids and deteriorated areas, and at the same time minimizing the potential risks of harmful hydraulic fracturing or weakening of earthen cores (FERC, 2016; Fell et al., 2015; K-water Research Institute, 2016a; Schaefer et al., 2011; Stare et al., 2012b; U.S. Army Corps of Engineers, 2014; USBR, 2012). Therefore, it is not desirable to use pressure-type grouting methods such as jet grouting, vibro-type compaction grouting, rock-mass pressure grouting, etc.

Typical dam remediation measures involve drilling and grouting methods (e.g., compaction grouting and jet grouting), deep soil mixing (e.g., conventional deep mixing, the trench remixing deep wall method, and cutter soil mixing), trench excavation and backfilling with an engineered material, composite cutoff walls, and upstream or downstream buttress structures for embankment stabilization (Bruce, 2012). Among these methods, the drilling and grouting methods can be useful to remediate deteriorated core layers and improve permeability when reservoir water draw-down is not possible. Relatively stiffer soil-crete or soil-cement wall structures may not be desirable in some cases because the relatively large stiffness contrast between the reinforced wall and existing embankment soils may unfavorably redistribute stress and impact long-term deformation behavior (Lim et al., 2004). In this study, drilling and grouting methods were selected on the dam crest because

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Table 1
Permeation grouting procedure for DB dam core layer remediation.

Sequence	Procedure
Pilot hole drilling ↓	NX-sized no-water boring, accompanied by core sampling, standard penetration test (SPT), and in-situ permeability test
Pilot hole grouting ↓	Upward grouting (1 stage: 5 m) Grout mix ratio and grout materials follow specified injection pattern
General hole drilling and grouting ↓	BX-sized rotary washed boring, grouting work based on pilot hole testing results that determined the appropriate maximum amount of grouting, injection duration, and grout mix ratio
Determination of additional remediation area ↓	Finding additional remediation areas by additional borehole drilling and grouting, following the same procedure as pilot holes
Bentonite remediation on the crest area ↓	Upon observation of highly permeable granular materials at approximately 3 to 5 m below the dam crest, bentonite injection (with a mix ratio of 3% bentonite in the water) was performed down to a depth of 5 m
Determination of check holes ↓	Locating equally spaced check holes, adjacent pilot holes, and additional investigation holes
Check hole drilling and grouting ↓	NX-sized no-water boring, accompanied by core sampling, chemical reaction tests, and in-situ permeability tests; after check hole investigation, final grout injection is made with a cement-to-water mix ration of 1:1
Electrical resistivity survey ↓	Verification of remediation grouting
Report writing	Reporting on the remediation grouting results

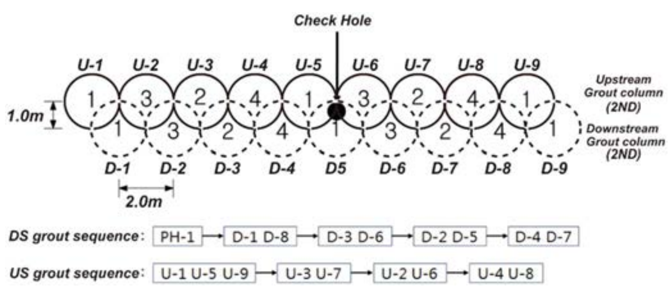

Fig. 1. Remedial grouting sequence applied to DB dam.

these methods are expected to effectively remediate core layer permeability if applied correctly.

Types of cementitious grout materials range from high-mobility grouts (low viscosity water-like grouts such as a cement slurry) to low-mobility grouts (stiff mortar-like grouts) (Stare et al., 2012a). As the void or fracture opening becomes smaller, high-mobility grouting becomes more effective. High-mobility grout is further classified as either neat cement grout or balanced stable grout (cement, water, and admixtures to mitigate bleeding and negative pressure filtration). Balanced stable grouts can typically be used for high-mobility remediation grouting of embankment core layers. Because typical core material is predominantly composed of fine grained soils, high-mobility grouting can be particularly effective in permeation grouting; Permeation grouting is a method by which a grout gradually permeates the soil voids before the grout starts to harden or set and cement the soil particles together (Idriss and Boulanger, 2008). This method has been applied extensively (Granata et al., 2012; Littlejohn, 2003); however, the method has not often been applied to dam embankment remediation (Bruce, 2012). Empirically established technical guidelines or criteria for applying remedial permeation grouting have not yet been proposed.

In this study, a low-pressure permeation grouting method is adopted as a clay core remediation measure. A total of five existing dam remediation cases are discussed in detail. All dams in this study are central core-type fill dams. Technical descriptions of each dam's seepage-related problems are provided. In practice, the deteriorated areas of the clay core layers are not uniformly distributed; rather, the deteriorated areas are randomly distributed, which complicates grouting designs and requires flexibility in the application of the grouting technique. Therefore, the grouting specifications for each case history vary depending on the characteristics of their respective core materials, voids, and degrees of deterioration. The comparative study of each dam remediation case informs empirical standards for the recommended permeation grouting methods, including grout mix, injection period per stage, injection rate, and maximum fluid pressure to prevent hydraulic fracturing. These empirical standards for successful low-pressure permeation grouting, which have never before been proposed, constitute the primary contribution of this study, and the standards can be applied to substantially improve a dam's core layer permeability and efficacy as a water barrier.

2. Proposed methods

2.1. Design and application of remedial grouting

An important potential risk with embankment grouting work is hydraulic fracturing, defined as the fracturing of an embankment by pumping pressurized water in excess of the tensile strength and minor principal stress of the embankment material (U.S. Army Corps of Engineers, 1984), or the tensile failure of an embankment induced by pressurized fluid from the drilling process (Stare et al., 2012a). Even grout pressures such as those suggested in this paper may result in hydraulic fracture when the lateral stresses in an embankment are lower than the vertical stress, owing to the arching of the core onto a stiff filter and differential settlement in the cross valley direction (ICOLD, 2015). To avoid hydraulic fracturing, the grouting pressure on the embankment should be carefully controlled within quantifiable limits (Stare et al., 2012b). Technical guidelines for drilling and sampling in embankment dams before remediation grouting should also be followed (FERC, 2016; U.S. Army Corps of Engineers, 2014; USBR, 2012). Although the relevant guidelines are much disputed (Schaefer et al., 2011; Weaver, 2000), the U.S. Army Corps of Engineers suggests that a safe grouting pressure is approximately 11.3 kPa/m for the overburden soil thickness and approximately 22.6 kPa/m for depth into rock (Schaefer et al., 2011).

For remediation grouting of dam embankment cores, a different design concept is required compared to the pressure grouting applied to dam foundations or coffer dam remediation. The most important difference is in the fluid pressure and refusal criteria. As applied to degraded earth cores, remedial permeation grouting should use very low pressure relative to other applications and appropriate refusal criteria

Table 2
Case study dam specifications, observed deterioration, and remediation measures.

Dam	WM	AG	DB	YC	HD
Construction period (year.month)	1985.12–1993.06	1968.08–1971.12	1986.11–1990.05	1977.12–1979.12	Built in 1984.12 Raised in 2004.12
NHWL (EL. m)	150.0	43.9	112.0	48.0	59.0
Reservoir capacity (mil. m^3)	135	18	8	5	0.9
H (m)	55	32.5	55	24.5	35
L (m)	407	223.5	326	120	315
Hazard type	Exposed event 1998.04–10: Three sinkholes found near crest, excessive leakage	Exposed event 1985.06: Wet zone found on the downstream slope; 2003.07: Downstream slope failure after intensive rainfall	Internal deterioration 2013.08: Locally fluidized cores found during borehole investigation; cores with coarse-grained materials near crest	Internal deterioration 2013.08: Locally fluidized or weakened cores found during borehole investigation	Exposed event 2014.10: Leakage found on the downstream berm and extensive wet zones found on the surface
Initial remediation	2000.05–08: Partial compaction grouting (L80 m)	1986.07–1989.05: General grouting 4 times; 2003.08–10: Downstream slope failure and emergency slope protection	–	–	–
Ultimate remediation	2003.04–09: Permeation grouting	2004.05–10: Permeation grouting	2014.04–10: Permeation grouting and upper crest bentonite injection	2014.09–12: Permeation grouting	2015.05–10: Permeation grouting and upper crest bentonite injection

Note: NHWL = normal high water level, EL. = elevation, H = dam height, L = dam crest length.

to prevent hydraulic fracturing and to maximize groutability. The grouting refusal criterion is typically expressed as the injection rate at which grouting is stopped, and the criterion is important for reaching the target permeability reduction. The traditional refusal value for rock grouting at a given stage varies from near zero to approximately 28.3 l or less in 5 to 15 min (Stare et al., 2012a), although this is contentious (Warner, 2004). Upstage grouting methods generally start with grout hole drilling, and then the hole is grouted in stages starting from the bottom in increments of approximately a few meters. The hole stability is critical to determining if an upstage or downstage grouting method is appropriate.

Before the dam remediation applied in this study, all of the dams showed some type of core material deterioration or adverse incidents. The common feature among all dams was the degraded impermeability of their core layers, and the degrees of deterioration were largely inhomogeneous and anisotropic. Therefore, site-specific remediation grouting designs and applications were essential. Initial remedial grouting design conditions were carefully arranged according to the pilot grouting test results. Additional findings obtained through additional trial tests were applied to correct the initial grouting design conditions. Specific criteria for maximum fluid pressure, grouting duration, and refusal were determined to prevent hydraulic fracturing and grout penetration into filter layers.

Table 1 and Fig. 1 show a typical procedure and a sequence of remedial permeation grouting, respectively, which were applied to a DB dam. For pilot hole drilling and sampling, the no-water boring technique was applied to avoid the risk of weakening the core material. In comparison to the typical rotary wash boring, this approach requires a boring machine with relatively more capacity and power, insofar as no water is used as a working fluid. Two rows of grouting holes were spaced 2 m from each other in the dam axis direction and 1 m from each other in the stream direction. The grouting sequence was conducted by interpolation with each incremental grouting spaced at least 8 m from the preceding one. For the remedial grouting of an AG dam, three rows of partial grouting holes were drilled, considering a relatively higher degree of core deterioration. The same procedure of drilling two rows of grouting holes, with or without upper crest bentonite grouting, was applied to the other dams in this study.

2.2. Features of dams in this study

Table 2 shows the basic dimensions, construction periods, deterioration, initial remediation measures, and dates of final remediation with a permeation grouting scheme for the five large earth-cored embankment dams investigated in this remediation case study, which are named as WM, AG, DB, YC, and HD dams, respectively. Among the dams, the WM, AG, and HD dams exhibited distinct incidents such as sinkholes, slope failure, excessive seepage, etc., whereas the DB and YC dams showed randomly developed fluidized cores of high water content with or without granular cores in the area adjacent to the dam crest. Fig. 2 shows typical cross-sections of the dams (K-water Research Institute, 2016b).

The WM dam is a 55-m-high earth-cored rockfill dam that exhibited distinct deterioration in the form of three sinkholes near the dam crest, which were observed over six months during normal dam operation (Fig. 3). Before any remediation, the dam seepage measured at the downstream toe increased up to approximately 2340 m^3/day at normal high water level (NHWL) (EL: 150.0 m). After an in-depth diagnosis, an initial remediation measure was applied by compaction grouting on 80 m out of the dam crest's total 407 m (Chun et al., 2006; Lim et al., 2004; Yea et al., 2012). After compaction grouting, the total seepage was reduced to 860 m^3/day near NHWL. However, two and a half years later, seepage had increased to up to 1007 m^3/day and another in-depth diagnosis revealed diversified flow paths within the embankment, which required remediation to be applied over the whole length of the dam. The final remediation was conducted using low-pressure

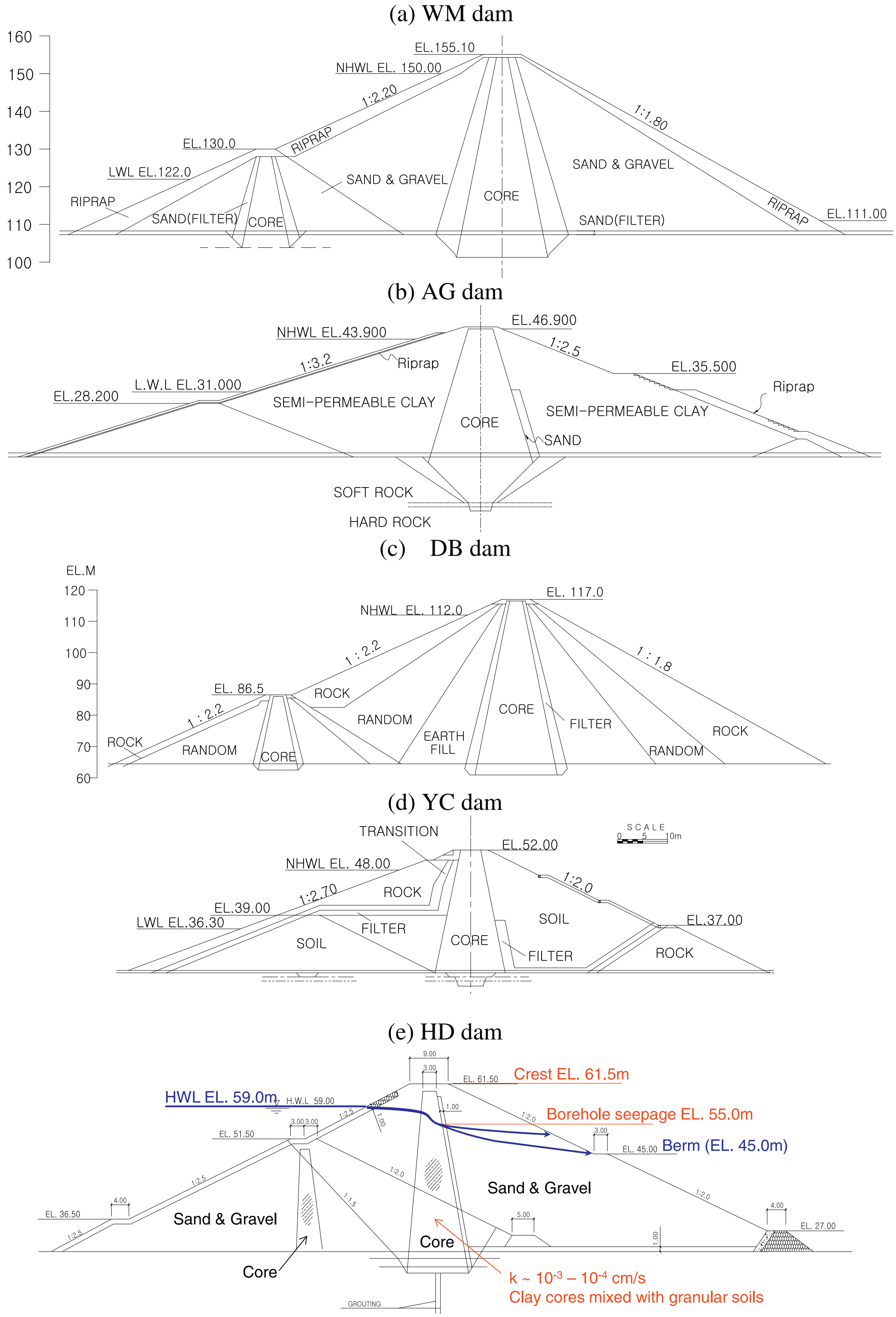

Fig. 2. Typical cross-sections of dams in this study (k = permeability coefficient).

permeation grouting.

The AG dam also showed distinct symptoms of core deterioration after first impoundment. The dam embankment's earthfill had very low stiffness and the core material contained a relatively large proportion of sandy soil with fine-grained soils. Various areas of wet zones were found on the downstream surface and remedial grouting applications were performed four times without any technical consideration of the embankment's state. As a result, heavy rainfall in 2003 induced significant downstream slope failure (Fig. 4). After implementing immediate emergency measures to rehabilitate the slope, permanent remediation was undertaken with permeation grouting.

In contrast, the DB and YC dams revealed no external symptoms of core layer deterioration. Instead, the core layer's deterioration was locally confirmed during a comprehensive geotechnical investigation that

Sinkhole (June 1998)	Sinkhole (September 1998)	Sinkhole (October 1998)

Fig. 3. WM dam sinkhole incidents.

Fig. 4. AG dam incident: downstream slope failure (2003).

included direct borehole drilling and sampling using a no-water boring technique (Park and Oh, 2016a, 2016b). Among the degraded samples of clay core layers, there were areas that were almost fluidized, core material with very high water content, and core material containing a large portion of granular coarse materials (Figs. 5 and 6). Fig. 7 shows results of a 3D electrical resistivity survey of the DB dam, depicting a low-resistivity area of < 50 Ω-m. To prevent the development of any preferential flow paths inside the core layer, remedial measures were reviewed. For the final remediation of these dam embankments, low-pressure permeation grouting was applied (Park and Lim, 2016).

The particle size distribution of the core and filter for each dam is useful to determine whether no-erosion criteria are met. According to the ICOLD (2015), the filter material should satisfy both geometrical and hydraulic conditions: coarse-layer pores have to be sufficiently large to allow particles to pass through, and the flow velocity has to be sufficiently rapid to detach the particles and also to transport them. The approach in ICOLD (2015) mainly uses the DB95 base soil sizes and DF15 filter sizes (DB95 = a soil diameter corresponding to 95% finer than the base soil, DF15 = a filter soil diameter corresponding to 15% finer than the base soil). For fine grading from particle size distribution of the YC, DB, AG, and WM dams, the DB95 is 0.24, 0.21, 4.3, and 3.2 mm respectively. Thus, the 9 DB95 of these soils are 2.2, 1.9, 38.7, and 28.8 mm respectively. If the DF15 is greater than the 9 DB95 values, then continuing erosion should have occurred. Unfortunately, the DF15 values are unknown for the dams considered in this study. However, the AG and WM dams showed a much coarser grain than the YC and DB dams, which might have contributed to the formation of sinkholes or slope failures.

The HD dam also exhibited extensive wet zones on the downstream surface. Leakage water was distinctively observed on the downstream berm near one-third of the dam height from the crest (Fig. 8). The clay core material was in poor condition, and the reservoir water level was operated near NHWL. After an in-depth geotechnical investigation and diagnosis, to remediate the core layer permeability, permeation grouting and bentonite injection were performed at the upper crest area.

Accurate reasons for the deterioration of the five dams are

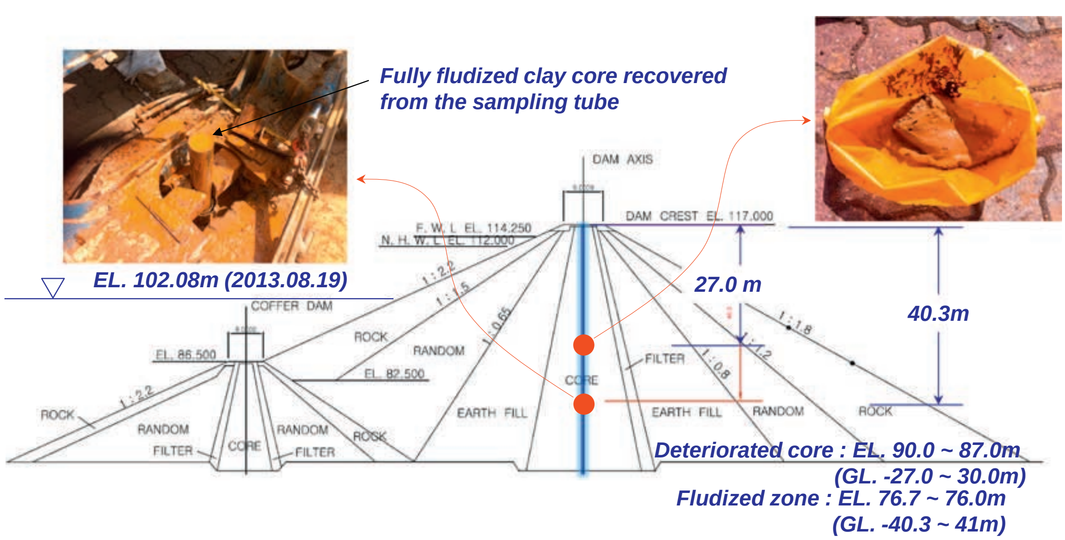

Fig. 5. DB dam: deteriorated core samples discovered during geotechnical investigation (2013).

Fig. 6. YC dam: locally deteriorated core samples discovered during geotechnical investigation (2013).

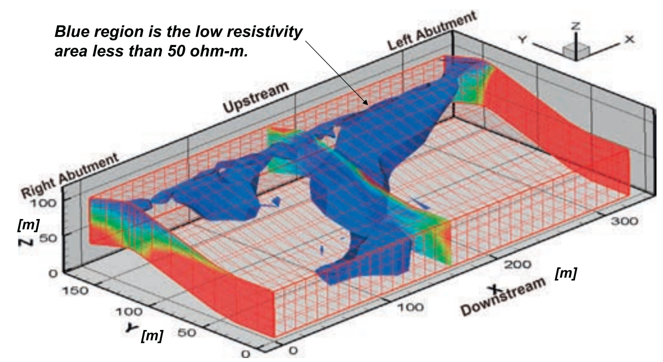

Fig. 7. Results of 3D electrical resistivity survey of DB dam, showing the low resistivity area of < 50 Ω-m.

uncertain, but some causes can be inferred based on the extensive geotechnical investigation program of each dam.

According to the electrical resistivity survey of all five dams, significant heterogeneity appears with very low resistivity values. As a result of the extensive geotechnical investigation programs, the AG and HD dams showed a very weak and permeable core and shell materials, and contained a relatively rich portion of sandy material. The WM dam also showed relatively lower local core stiffness with a normalized SPT blow count ($N_{1,60}$) of < 8. For the DB dam in the bore hole drilling and sampling investigation, a locally fluidized zone and relatively lower core stiffness were found, as well as an earth core with granular coarse materials. Based on a soil laboratory test of the core samples, the natural water content (w = 30.6%) and plasticity index (PI > 30%) of the DB dam cores were relatively higher than the average of other dams (w = 24%, PI = 16%). The $N_{1,60}$ for the DB dam cores was much lower (~8) than the average for the dams in the investigation (~14). For the YC dam, a locally fluidized zone and relatively lower SPT N values were found.

Therefore, the primary causes of deterioration can be reasoned as follows: (1) inappropriate construction material used locally (for the WM, DB, AG, and HD dams); (2) incomplete compaction (for all five dams, and especially for the DB, AG, and HD dams); and, probably, (3) arching between the relatively narrow cores and stiff filter zones and its harmful effect during the first filling (for the WM, DB, YC, and HD dams). The common cause might be the interaction of a complex set of reasons pertaining to permeable core materials, less compaction, and arching. However, the consequences of these phenomena are exhibited differently depending on the degree of heterogeneity of the causes and how much they are distributed locally or globally.

3. Results of remedial permeation grouting

3.1. Application of remedial permeation grouting

Table 3 summarizes the specific applications of the low-pressure permeation remedial grouting techniques applied to each of the five different central earth-cored dams. In Table 3, details of the empirically proven technical specifications are addressed, including maximum grout fluid pressure, grouting duration, the initial grout mix ratio, the grout mix change condition, refusal criteria for every stage, the fluid pressure change condition, and the additive ratio.

As the main grout material, either ordinary Portland cement (OPC) or micro-cement (MC) was used depending on the groutability, void ratio of the core material, and the degree of core material degradation. For the WM dam remediation, two different criteria between those associated with OPC and MC were applied, depending on the type of cement material.

Although different grouting designs were applied, Table 3 reveals a common standard that should be applied to the maximum grout fluid pressure to avoid hydraulic fracturing in remedial permeation grouting. In these empirical applications, a maximum fluid pressure of 2×10 kPa/m $\times$ depth (m) $\times$ 0.75 was proposed (Lim et al., 2004). This equation can be interpreted as saying that the maximum fluid pressure is approximately 75% of the hydraulic fracturing pressure at the given depth, with a minimum pressure of 10 kPa per unit depth. Therefore, the maximum fluid pressure increases with depth, limited to 100 to 500 kPa depending on the dam height. Importantly, the pressure referred to is the pressure at the section being grouted, and not the pressure at the surface.

The grouting injection duration per meter in depth varied depending on the depth; in general, the grouting duration was determined to be 8 to 40 min for grouting depths of < 40 m. The commonly applied injection fluid rate was 5 to 20 l/min, and the initial grout mix ratio for core layers was mostly 1:3 or 1:2, as a mass of cement relative to that of

Fig. 8. HD dam: leakage and wet zones observed on the downstream surface.

Table 3
Design and application details of permeation grouting for dam core remediation.

Dam	WM		AG	DB	YC	HD
	OPC	MC				
Max. fluid pressure (kgf/cm^2)	2–5	2–5	1–4	1–3	1–2	2–3
Grouting duration (min/m) (DS: downstream row; US: upstream row)	Varied from 8 min for $z \le 10$ m to 40 min for $z > 40$ m	Varied from 8 min for $z \le 10$ m to 40 min for $z > 40$ m	Varied from 5 min for $z \le 10$ m to 45 min for $z > 45$ m	(DS) 10 min for $z \le 20$ m, 15 min for $20\ m < z \le 35$ m, 20 min for $35\ m < z \le 50$ m (US) 5 min for $z \le 20$ m, 10 min for $20 < z \le 35$ m, 10 min for $35\ m < z \le 50$ m	(DS) 10 min for $z \le 20$ m, 15 min for $20\ m < z \le 30$ m (US) 5 min for $z \le 20$ m, 10 min for $20\ m < z \le 30$ m	
Initial grout mix ratio (C: W)	1:4.5 for $z \le 20$ m, 1:3 for $z > 20$ m	1:2 for core embankment 1:1 for rock foundation	1:2 for core embankment 1:1 for rock foundation	(DS) 1:3 for $z \le 20$ m, 1:2 for $z > 20$ m (US) 1:3	1:3	1:3 for weaker areas, 1:2 for other areas
Grout mix change condition	(1st) when flow rate > 15 l/min: C:W = 1:3 for $z \le 20$ m after 5–10 min, C:W = 1:2 for $z > 20$ m after 10 min (2nd) when flow rate > 10 l/min: C:W = 1:2 for $z \le 20$ m after 5 min, C:W = 1:1 for $z > 20$ m after 10 min (3rd) when flow rate > 8 l/min: C:W = 1:1 for $z \le 20$ m after 3–5 min, keep C:W = 1:1 for $z > 20$ m	Keep C:W = 1:2 constantly	(1st) when flow rate > 55 l/min for 5 min at 1 kgf/cm^2: C:W = 1:1 for core embankment, C:W = 1:0.8 for rock foundation (2nd) when flow rate ≤ 10 l/min at the max fluid pressure: C:W = 1:3 for core embankment, C:W = 1:2 for rock foundation	Keep C:W = 1:2 or 1:3 constantly; change only fluid pressure and grouting duration	Keep C:W = 1:3 constantly; change only fluid pressure and grouting duration	Flexible mix change from high to low mobility depending on the groutability in-situ
Fluid pressure change condition	Stop injection when there is no flow rate decrease, re-inject after not < 4 h	Keep low pressure when flow rate > 20 l/min at low pressure; stop injection when there is no more flow rate decrease and re-inject after 4 h	Increase fluid pressure when flow rate ≤ 10 l/min for 5 min at each pressure stage; maintain the pressure when flow rate is 10–55 l/min for 5 min at each fluid pressure increase; decrease fluid pressure when flow rate > 55 l/min for 5 min at each fluid pressure increase	For $z \le 20$ m, keep pressure at 1 kgf/cm^2; for z = 20–35 m, keep pressure at1 kgf/cm^2 when flow rate > 10 l/min, and increase pressure to 2 kgf/cm^2 when flow rate ≤ 10 l/min; for $z > 35$ m, keep pressure at 2 kgf/cm^2 when flow rate > 10 l/min, and increase pressure to 3 kgf/cm^2 when flow rate ≤ 10 l/min	For $z \le 20$ m, keep pressure at 1 kgf/cm^2; for z = 20–30 m, keep pressure at 1 kgf/cm^2; when flow rate > 10 l/min, increase pressure to 2 kgf/cm^2; when flow rate ≤ 10 l/min	Lift the casing by 1 step (0.5 m) when flow rate < 5 l/min during max fluid pressure at a certain grouting step

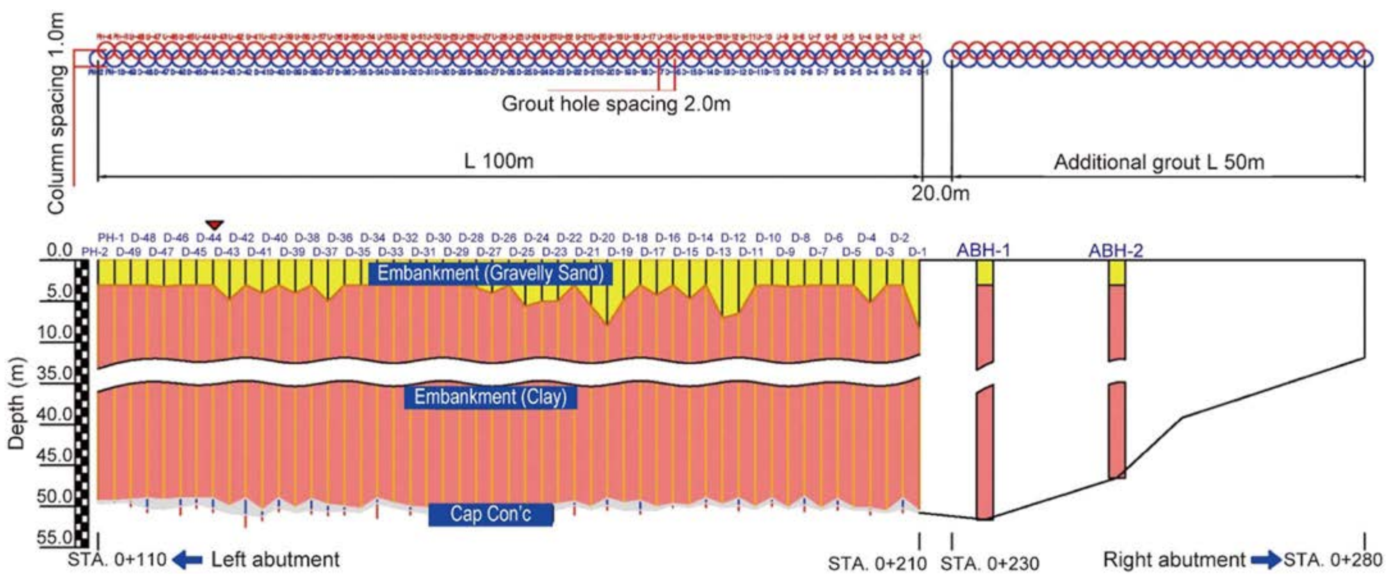

Fig. 9. Soil strata in DB dam embankment.

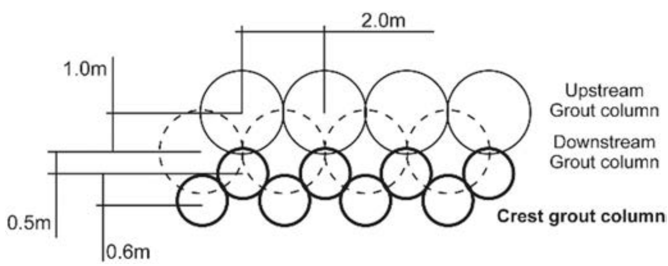

Fig. 10. Bentonite grouting scheme for near crest area of DB dam.

water. The grout mix ratio gradually varied up to 1:1 depending on the in-situ condition. The grout mix change criteria during grouting were applied differently depending on the in-situ conditions of the dams; however, in all cases, the flow rate was an important factor in considering changes to the cement-to-water ratio. In some cases, the grout mix ratio was kept constant, and the fluid pressure and grouting duration were adjusted accordingly.

The grouting refusal criteria for every 5-m stage was selected primarily to limit the maximum injection quantity in liters (e.g., 800–1000 l maximum for the WM dam, 800–1000 l maximum for the AG dam, 800–1500 l maximum for the DB and YC dams, and 500–1000 l maximum for the HD dam). The fluid pressure change conditions varied a lot for each dam; however, a common approach was to set the pressure value in conjunction with the flow rate (l/min) condition at each depth as shown in Table 3. Incremental fluid pressure was typically maintained for at least 3 min when increasing the pressure. For the DB and YC dams, the casing was lifted by 1 step (0.5 m) when the flow rate < 3 l/min at a certain grouting step.

For the DB and HD dams, in addition to core layer permeation grouting, geotechnical investigations including borehole drilling and sampling and trench excavation on the crest revealed that significant amount of relatively granular coarse materials were mixed with clay cores adjacent to the NHWL, which may threaten the stability against seepage flow during reservoir operation at higher water levels (Fig. 9). Therefore, it was necessary to fill the large void near upper crest level; bentonite permeation grouting was selected to remediate the upper crest areas following the scheme shown in Fig. 10.

3.2. Results of remedial permeation grouting

Table 4 shows the results of dam core layer remediation by low-pressure permeation grouting for the dams in this study. Three dams (WM, AG, and HD) that exhibited distinct dam incidents during operation were remediated over the entire crest length of the dams, whereas the other two dams (250 m out of 320 m for the DB dam, and 60 m out of 120 m for the YC dam) were partially remediated. The

Table 4
Results of dam core remediation by permeation grouting.

Dam	WM	AG	DB	YC	HD
No. of grout holes	404 Pilot 10 General 361 Check 33	293 Pilot 6 General 280 Check 7	261 Pilot 6 General 95 Check 10 Additional 150	70 Pilot 2 General 39 Check 4 Additional 25	252
Total grout length (m)	16,932	11,131	11,538	1584	7611
Total grout quantity (m^3)	1544	825	764	129	
Total cement quantity (kg)	690,493 OPC: 94,170 MC: 596,323 Bentonite: 30,718	437,362 MC: 424,139 Bentonite: 13,223	305,489 (MC and Bentonite)	40,572 (MC and Bentonite)	631,700 (OPC, MC, and Bentonite)
Avg. grout quantity (l/m)	91.2	74.2	66.2	81.7	
Avg. flow quantity (l/min)	23.9	18.2			
Avg. cement quantity (kg/m)	40	39	26.5	25.6	82.9
Avg. cement quantity (kg/min)	11	9.7			
Mixer RPM (min)	800	1600	800	800	

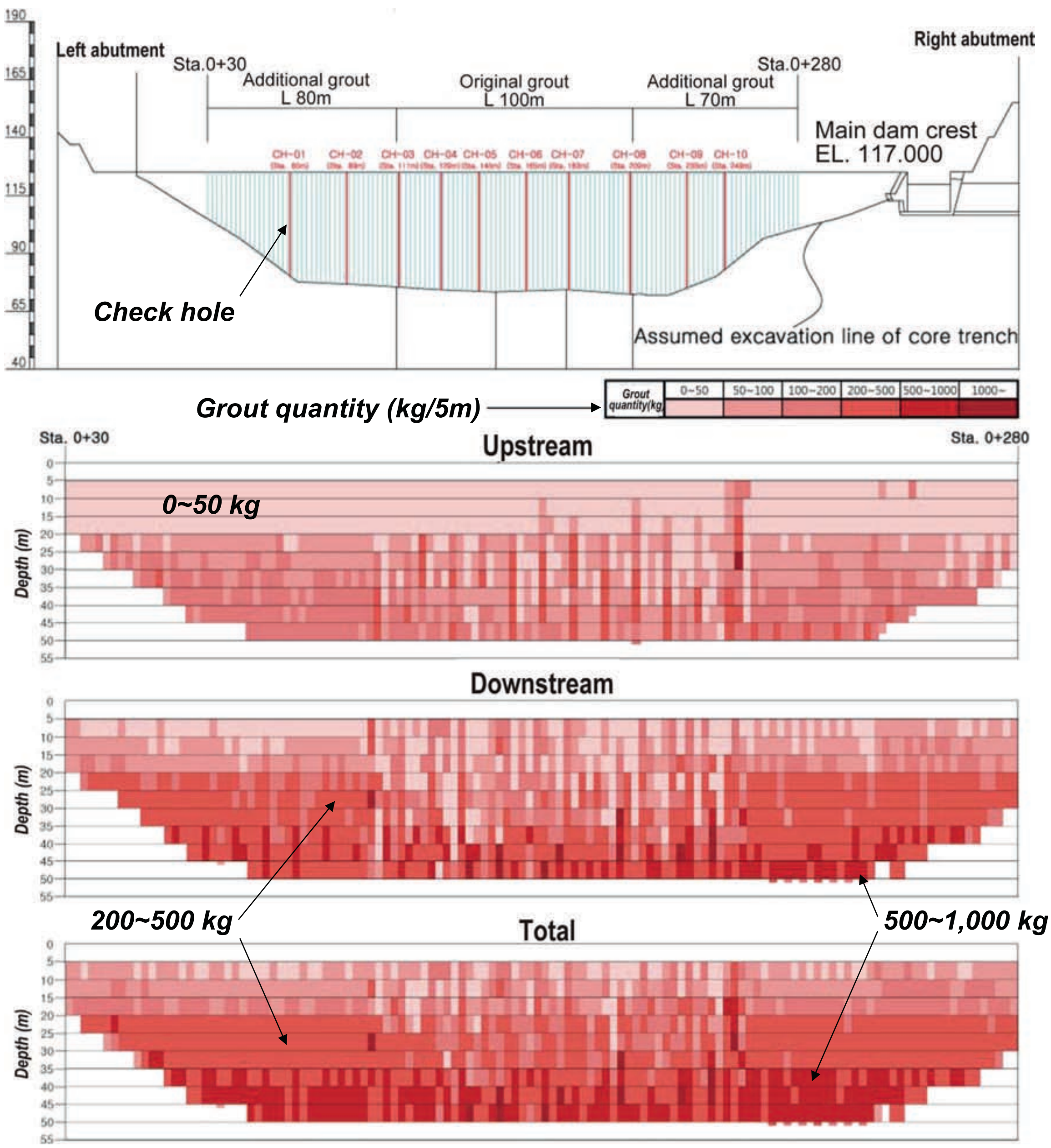

Fig. 11. Remediation grouting area, injection map, and check hole location for DB dam.

grouting depth reached to the bottom of the foundation rock mass.

The majority of the grout material was MC; however, OPC was also used in the WM dam, which had sinkholes and granular cores, and in the HD dam, which exhibited excessive leakage. To stabilize the grout holes and mitigate bleeding during remedial grouting, up to 5% bentonite was added to the mix, and this addition was found to be effective.

The average amount of cement used per meter (kg/m) was much higher for the HD dam, at 83 kg/m, than the 39–40 kg/m used for the AG and WM dams, which showed distinct incidents, and approximately 26 kg/m for the DB and YC dams, which showed internal degradation of core materials (Table 4). The HD dam required more cement because its core material quality was the worst among the dams. The average grouting quantity was varied from 18 to 24 l/min for the WM and AG dams, and from 66 to 91 l/min for the DB and YC dams. Figs. 11–13 illustrate the results of remedial permeation grouting for the dams.

For the DB and HD dams, in addition to permeation grouting in the cores, bentonite grouting of the upper part of the granular core layers near the dam crests was expected to further enhance the stability against seepage flow in case of dam operation near NHWL. Fig. 14 shows the result of remedial grouting with bentonite near the upper crest area.

4. Validation and discussion of grouting effect

Because the remedial grouting state is not visible underground, remediation work is not easily validated quantitatively. However, a limited validation can be attained by visual inspection of the surface, checkhole drilling and sampling, analysis of the sampled core's reaction to chemical indicator spray, in-situ permeability testing, analyses of grout quantities and total seepage rate change at the dam toe, and electrical resistivity surveys.

Table 5 shows the results of the remedial grouting validation. Visual inspection during checkhole drilling and sampling for the WM, BD, and YC dams showed a good core sample recovery. For the AG and HD dams, which exhibited distinct wet zones on the downstream surfaces, visual inspection after grouting showed the dry state of the previously

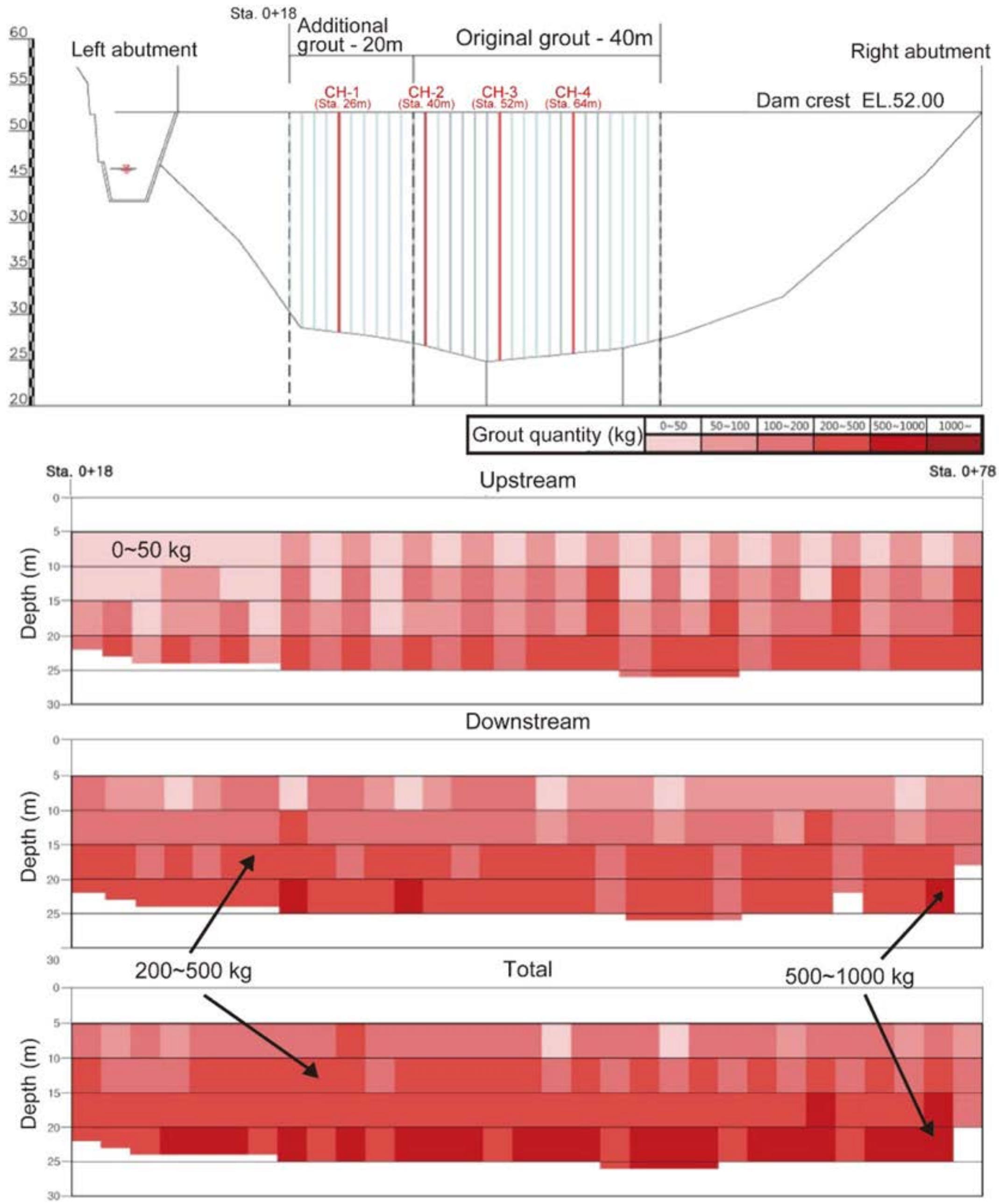

Fig. 12. Remediation grouting area, injection map, and check hole location for YC dam.

wet surface soils. For all five dams, chemical indicator reaction tests were performed on checkhole core samples using Phenolphthalein spray. It was observed that the area penetrated by the grout milk turned red after application of the Phenolphthalein spray, indicating a good filling of soil voids (Fig. 15).

Based on in-situ permeability measurements during the checkhole drilling process, all dams showed less core layer permeability after remedial grouting. The maximum permeability coefficient (k) before remediation of approximately 10^{-4} cm/s was reduced down to approximately 10^{-5} cm/s.

The average remediation grout flow rates of the general and check holes were comparable; however, different cement quantities were required for grout injection in downstream row holes and in upstream row holes. For the DB and YC dams, the cement quantity required for the downstream side, which was remediated first, was much larger than that of the upstream side.

The seepage rate measured at the center of the downstream toe after remediation grouting decreased remarkably for WM and AG dams, indicating successful permeation remedial grouting.

Electrical resistivity surveys were conducted for some dams in this study, as shown in other references (Panthulu et al., 2001; Sjödahl et al., 2008). Overall, after remediation, uniformly increasing patterns of resistivity distribution were found as depth increases. Although qualitative validations were easily accomplished, this quantitative validation of remedial grouting through the electrical resistivity survey remained challenging because of the possibility of biased results induced by the effects of geometry and material properties (Sjödahl et al., 2006), electric charge characteristics of core clays, reservoir water levels and saturation degrees, noise from embedded electrical cables, and low-resistivity features of cement-milk type grout materials.

Nonetheless, all of the validation findings support the effectiveness of remedial permeation grouting for the dams in this study. Since remedial grouting to the present time, these five dams have maintained their safety without any problem in their permeability of core layers.

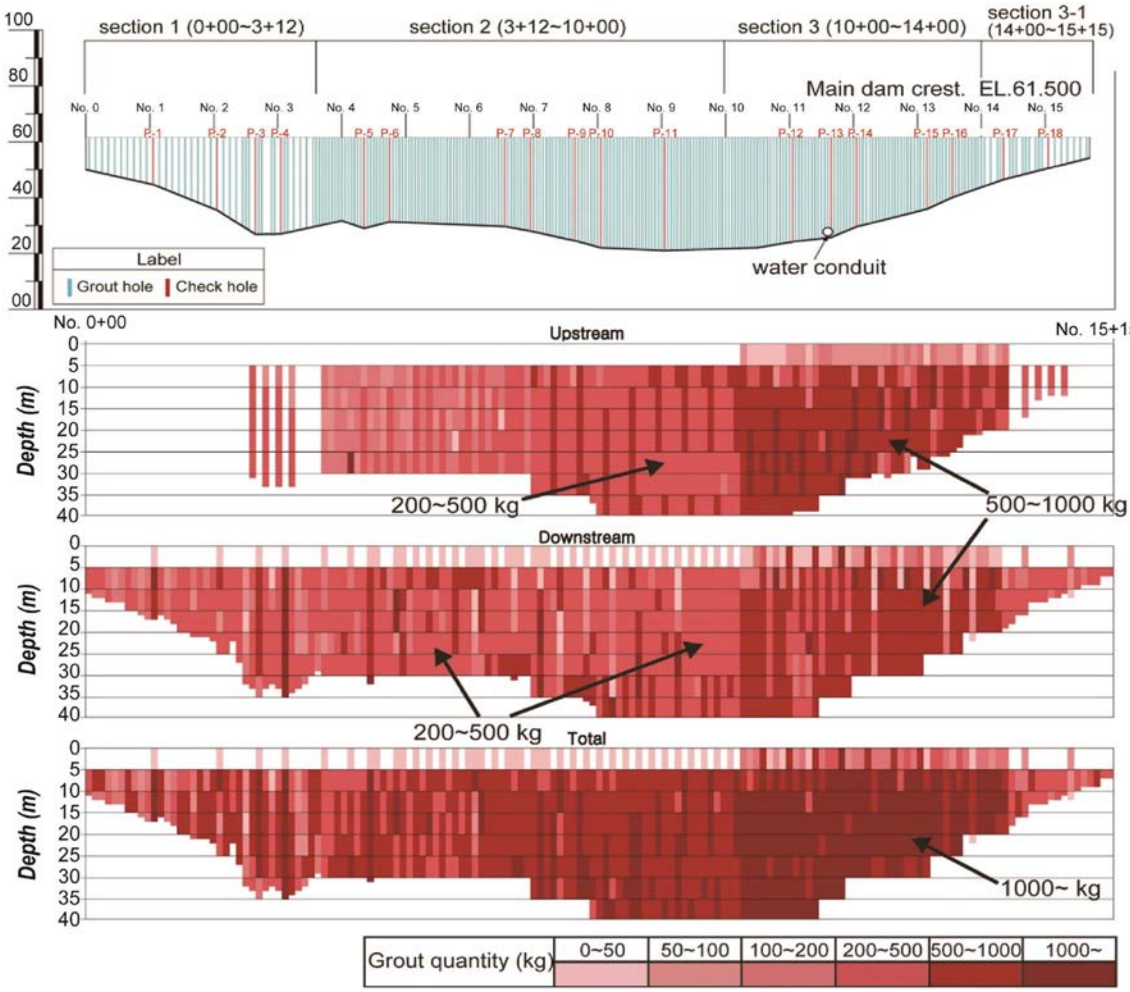

Fig. 13. Remediation grouting area, injection map, and check hole location for HD dam.

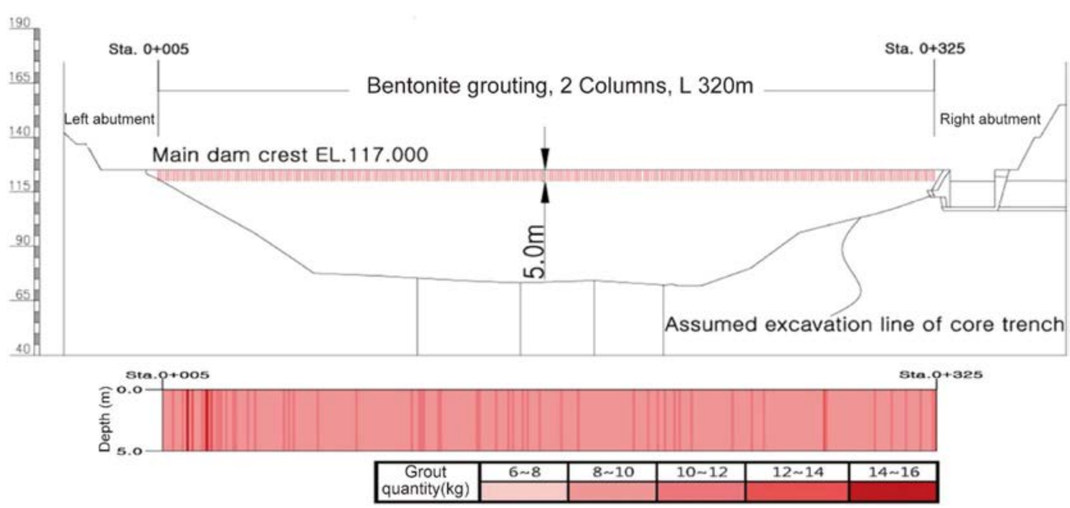

Fig. 14. Bentonite grouting result of DB dam crest area.

Remediation grouting of dam cores is demonstrated using a low-pressure permeation grouting technique that effectively remediates both fluidized and granular core layers. The empirical case studies in this paper are believed to offer an important reference for hazard mitigation technology in a wide range of aging dam rehabilitation projects.

5. Conclusions

This paper analyzed and discussed remedial grouting techniques applied over ten years to five existing deteriorated dam clay core layers. For remediation grouting of dam embankment cores, a totally different design concept is required compared to typical pressurized grouting applications, such as dam foundation or coffer dam grouting.

Table 5
Validation of the effect of remediation grouting.

Dam	WM	AG	DB	YC	HD
Visual inspection and borehole investigation	Good checkhole core recovery condition	Previously wet zones on the downstream surface become dry	Good checkhole core sample condition	Good checkhole core sample condition	Previously wet zones on the downstream surface become dry
Chemical indicator reaction	Confirmed by Phenolphthalein spray	Confirmed by Phenolphthalein spray	Confirmed by Phenolphthalein spray	Confirmed by Phenolphthalein spray	Confirmed by Phenolphthalein spray
Permeability measurement (cm/s)	Before, k ~ 10^{-4} max → After 10^{-5} max	Before, k ~ 10^{-4} max → After 10^{-5} max	Before, k ~ 1.47×10^{-4} max → After 1.19×10^{-5} max	Before, k ~ 9.36×10^{-5} max → After 9.80×10^{-6} max	Before, k ~ 3.79×10^{-4} max → After 5.16×10^{-6} max
Average flow rate (l/min) or grout quantity (kg/m)	24 l/min for general holes → 28 l/min for check holes	18.8 l/min for general holes → 14.5 l/min for check holes	Cement quantity, 39.7 kg/m for DS row → 13.1 kg/m for US row	Cement quantity, 31.4 kg/m for DS row → 19.3 kg/m for US row	
Seepage rate (Q) (m^3/day)	For reservoir water level = EL:147 m, Q = 640 m^3/day after 1st remediation by compaction grouting → Q = 4.1 m^3/day after 2nd remediation by permeation grouting	Leakage decreased remarkably after remediation, as measured by a temporary flowpipe-type device			
Electrical resistivity (ER)			Overall, uniform increasing pattern of resistivity distribution as depth increases	Overall, uniform increasing pattern of resistivity distribution as depth increases	Overall, uniform increasing pattern of resistivity distribution as depth increases

Remediation grouting without reservoir water drawdown is known to be effective; however, case history reports on this topic are rare, and no empirical standards for applying the method have been presented.

In this paper, low-pressure remediation grouting techniques were applied to five existing cored dam embankments that showed either exterior or interior deficiencies in core impermeability. The dams exhibited embankment deterioration of the following types: randomly distributed fluidized cores of high water content, wet downstream surfaces, sinkholes on the crest, downstream slope failure, or granular cores in the areas adjacent to the dam crest.

Various validation methods demonstrated that site-specific low-pressure permeation grouting can effectively remediate dams by improving the impermeability of deteriorated core layers. Fundamental empirically proven technical specifications are proposed, including limits on the grout pressure, grout flow rate, injection duration, initial grout mix ratio, additive ratio, and grouting condition change. Signature characteristics of the most commonly effective remedial permeation grouting techniques include the following.

- Two or three rows of grout columns on the crest, spaced 2 m apart in the dam axis direction and 1 m apart in the stream direction.
- Interpolated remedial grouting sequence of columns spaced at least 8 m from each other.
- Main grout material composed of ordinary Portland cement for sinkhole core filling, granular material grouting, and cores where severe leakage is occur; and micro-cement for other purposes.
- Additive material such as bentonite comprising < 5% of the mixture's mass quantity.
- A fluid injection rate of 5–20 l/min and a maximum fluid pressure of 100–500 kPa for depths within 55 m to prevent hydraulic fracturing and grout insertion into filter layers. The empirically proposed maximum fluid pressure (kPa) is formulated as 2×10 (kPa/m) $\times$ depth (m) $\times$ 0.75.
- A grouting duration of approximately 8–40 min for dams up to 40 m in depth.
- An initial grout mix ratio (C:W) of 1:3 or 1:2 for earthen cores, and gradual change of mix to 1:1.
- Grouting refusal criteria vary but are typically controlled by fluid pressure, flow rate, and grouting duration.

In addition to applying permeation grouting to the cores, bentonite grouting can be applied to the upper part of the granular core layer near the crest to stabilize the dam against seepage flow in case of dam operation near NHWL. The effects of the remedial grouting were validated by visual inspection and checkhole investigation, chemical indicator reaction, direct permeability measurement, average flow rate or grout quantity comparison, seepage rate observation, and electrical survey.

Finally, we emphasize that core grouting of embankment dams is a specialized technique and should not be undertaken without technical guidance from experts in grouting and in embankment dam engineering. If carried out incorrectly, grouting of dam cores has the potential to initiate hydraulic fractures, which can in turn lead to internal erosion and piping. Moreover, depending on the zoning of the dam and the filter compatibility with the core, this may lead to the failure of the dam. Readers should be aware that the lateral stresses in a dam may be lower than the vertical stress. This can occur due to arching of the core onto stiff filter zones, and differential settlements in the cross valley direction. In these circumstances, even the grout pressures suggested in this paper may result in hydraulic fractures.

The empirical case studies in this paper are expected to offer an important reference for hazard mitigation technology in a wide range of aging dam rehabilitation projects.

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Fig. 15. Chemical indicator reaction for HD dam checkhole core samples after remedial grouting.

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