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Permeation grouting for remediation of dam cores

DongSoon Park[a,b,*], Jeheon Oh[a]

[a] K-water Research Institute, 1689 Beon-gil 125, Yuseong-daero, Yuseong-gu, Daejeon 34045, Republic of Korea
[b] Dept. of Civil Engineering, California State University, Sacramento, USA

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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

* Corresponding author at: K-water Research Institute, 1689 Beon-gil 125, Yuseong-daero, Yuseong-gu, Daejeon 34045, Republic of Korea.
E-mail addresses: dspark210@gmail.com, fulgent@kwater.or.kr (D. Park), ojheon@kwater.or.kr (J. Oh).

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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

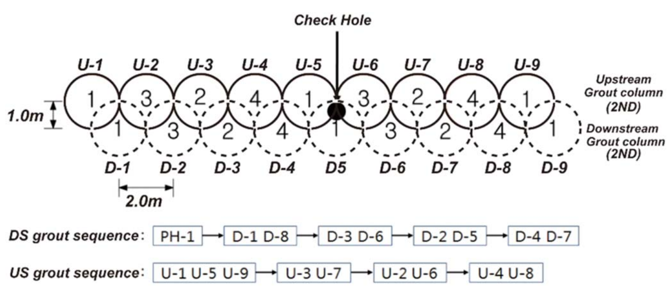

Fig. 1. Remedial grouting sequence applied to DB dam.

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

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