한국지반공학회논문집 제22권 11호 2006년 11월 pp. 13 ~ 23

# The Effects of Remedial Works to Control the Leakage Problem in Earth Fill Dam by Compaction Grouting

## 콤팩션 그라우팅에 의한 흙댐의 누수복원 공사효과 분석

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### 요 지

국내의 흙댐 중에서 댐코아에 함몰 및 누수가 발생한 사례가 있었는데 콤팩션그라우팅에 의하여 댐코아의 손상부위를 복원하였다. 본 연구에서는 콤팩션그라우팅에 의한 복원공사전 공사중 및 공사후에 실내 및 현장시험을 통하여 콤팩션그라우팅 효과를 평가하였다. 콤팩션그라우팅공사와 더불어 정밀한 현장조사 및 지구물리탐사를 진행하였다. 콤팩션그라우팅공사는 2000년 6월 16일부터 8월 24일까지 수행되었다. 콤팩션그라우팅공사에 의한 댐복원후에 댐코아의 누수가 감소되었다. 콤팩션그라우팅공사가 손상된 댐을 복원하는데 효과가 큰 것으로 평가되었다. 콤팩션그라우팅공법의 적용에 의하여 댐코아의 느슨하고 공간이 있는 부분을 채우게 되었고 그라우팅 처리전에 비하여 누수량이 약 96% 정도 격감 되었다.

### Abstract

The sinkhole and leakage in dam core were detected at one of earth fill dams in Korea. The damage areas in the core of the dam were repaired by compaction grouting method. This study is to evaluate compaction grouting activity by in-situ and laboratory experiments before, during and after the remedial work. The intensive site investigation and geophysical survey were conducted during and after the compaction grouting work. The compaction grouting work was carried out for the damaged dam core between June 16 and August 24, 2000. The leakage reduction generally occurred in the core of the dam after the remedial work. The use of compaction grouting was considered the proper countermeasures for repairing the damaged dam. It shows that the loose or voided zones have been properly filled and the leakage has been reduced by about 96% of that before the treatment of the remedial work performed at dam core by compaction grouting.

**Keywords** : Compaction grouting, Dam core, Earth fill dam, Injection, Leakage, Repair

## 1. Introduction

The earth fill dam studied in this paper was constructed in July 1993 in Korea. The dam typically consists of a clay core, filter zone and sandy gravel shell, and has a crest length of 407 m and a height of 55 m as

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* 본 논문에 대한 토의를 원하는 회원은 2007년 5월 31일까지 그 내용을 학회로 보내주시기 바랍니다. 저자의 검토 내용과 함께 논문집에 게재하여 드립니다.

shown in Figure 1 (Korea Water Resources Corporation, 2000; Lim et al., 2004). The dam reservoir was filled with water in October, 1993 and was full by 1998. A small cavity was discovered on the dam crest in June, 1998, when the reservoir water level rose to 150 m after the first impounding and the sinkhole developed in the dam body in July, 1999 at Sta. No. 10 and 12 of dam. Although the cavity and sinkhole was refilled by rubble and soil, the cavity and sinkhole continuously occurred. A comprehensive investigation was executed to characterize the leakage through dam body. The leakage of reservoir water was detected at lower stream of dam. The leakage is generally caused by insufficient basic foundation treatment in the process of dam building or dam's behavior such as tension cracks due to weight and water pressure and external corrosion by permeation. Irrigation facilities become weak or degraded by weight and external force as time elapses and this phenomenon causes safety problems of the facilities. Leakage problem, affecting safety of the irrigation facilities most, is caused locally rather than wholly. Infiltration, directly affecting disaster by damage of dam body or large leakage, is rather caused in water stratum than in layer. The water pressure in water stratum rises due to the sudden rise of water level by severe rain storm or typhoon, and it causes high pore water pressure in surrounding soil masses and movement of soil particles in partial. This process is called Piping, which mainly causes large leakage and destruction of dam body developing slope failure and makes trouble in farming starting from local damage.

Thus, the countermeasures and rehabilitation program were required to repair and treat this damaged and defected earth dam (Salembier et al., 1998; Seemel et al., 1976; Stewart et al., 1998; Weaver, 1993). The remediation of the damaged earth dam is complicated and risky due to difficulty of remedy for the damaged earth dam (Dhar, 2004; Salembier et al., 1998). There are many dam remedial measures such as grouting, cutoffs and surface sealing (Bernell, 1976). The grouting alternative was selected for the treatment of the damaged earth dam due to its complication function to the damaged dam core (Brown et al., 1973; Warner, 1982). Grouting remediation method is mainly used domestically and has many construction cases, but it is difficult to judge the effect of construction.

Generally, the soil becomes loose with time elapses because of the deterioration of the structure and abnormal drainage. As is widely known, compacting such loosened soil in new landfill area can prevent liquification, thus, the material for leakage remediation must interrupt the liquification to expand its range by capillary phenomenon requiring normally homogeneous material in mixing of soil or clayey soil. As a result of the investigation considering the ground condition, construction condition

Table 1. Comparison of compaction grouting and grouting method for application of leakage remediation

| Item | Compaction grouting | Grouting |
|---|---|---|
| Application method | Economical ground improvement method by transmitting high shock wave energy to coarse grained soil | Injects grouting material such as cement and clay to basic ground and solidify for the purpose of reinforcement and stagnant water of reservoir or dam and ground intensification and permeability of structure |
| Strong point | - Homogeneous improvement of ground<br>- Required ground strength is controllable<br>- Short construction period<br>- Economic<br>- Non-sandy soil production<br>- *Not necessary special material*<br>- Applicable to many kinds of soil such as core soil, sand and waste | - Clean remediation in original state without damage of the structure<br>- Stagnant water every portion that was unable to stagnant water by existing method |
| Bad point | - Operates by vibration and may affect surrounding structure<br>- May obstruct in operations of airplane | -Reoccur of leakage<br>-High prices cost |
| Reason for selection | High economic efficiency and constructability | |

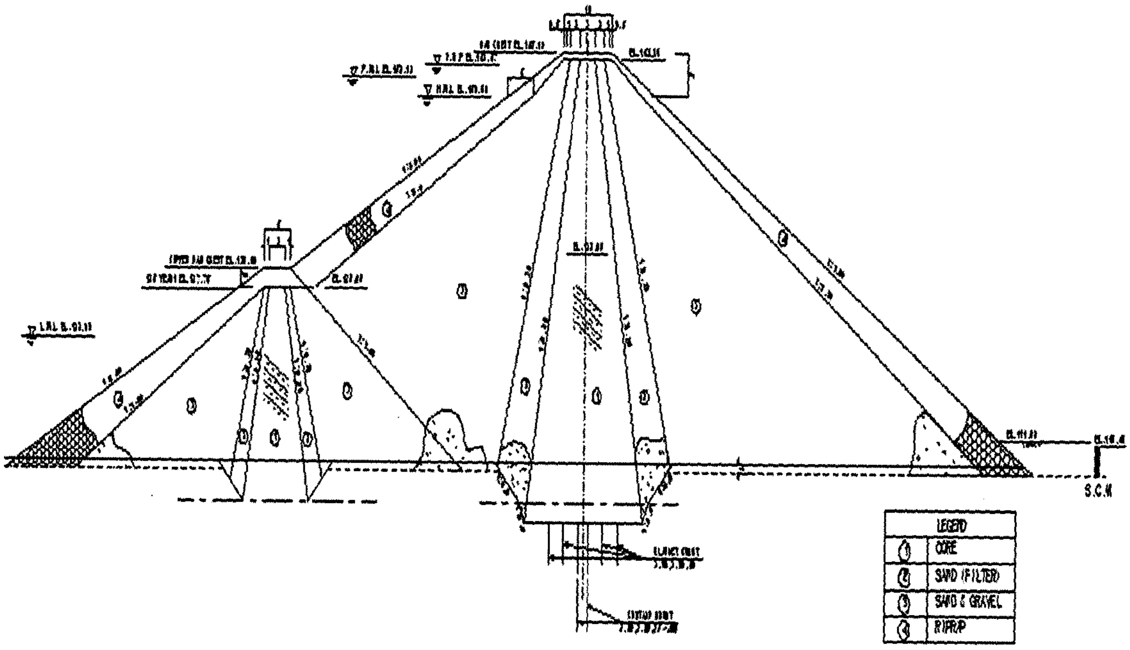



Fig. 1. Cross section of earth fill dam

and economic efficiency, it is concluded that compaction grouting is the more appropriate to this area than grouting method as shown in the Table 1.

Consequently, this study carried out compaction grouting for the purpose of 1) reducing compressibility for settlement reduction, 2) increasing bearing power for minimizing displacement of ground due to roadbed or saturation, 3) increasing shear strength for enhancing safety ratio on the destruction, 4) preventing liquification of ground. Compaction grouting is the remediation method that injects unliquid material to the ground to improve the loosened soil formed naturally or artificially by compressing and strengthening the neighboring ground. Therefore, it is fundamentally different from other injection method using active liquidity material.

The compaction grouting program was carried out from June 16 to August 24, 2000 based on the preliminary trial test. The leakage generally decreased after the completion of the compaction grouting. This paper aims to describe the application of the compaction method and interpret the monitored seepage, pore pressure and permeability before, during and after the remedial work.

## 2. Compaction Grouting Works

The exploration and rehabilitation were aimed to identify and to backfill the loose zones in the areas of the present sinkholes at Sta. No. 10 and 12 of dam. The rehabilitation program of earth dam consists of three stages; the exploration stage, the diagnosis stage, and the remedial stage (Korea Infrastructure Safety and Technology Corporation, 2005; Korea Water Resources Corporation, 2000; Lim et al., 2004, Sambu Construction Technology Co, 2000; Youngnam University et al, 2001). It appears compaction grouting can be selected as a repairing alternative to treat the damaged zones based on the results of exploration and diagnosis stages. The use of low mobility compaction grout was considered the safest program for repairing the dam.

Compaction grouting appears to have effectively closed and/or filled voids or channels and/or compacted loose soils that were present at Sta. No 10 and 12 of dam. The compaction grouting is the technique to inject low mobile grout into the ground using specially sized and modified hydraulic piston pumps. The grout pumps need to be capable of pumping low mobile grout, and slow injection is necessary to minimize the build-up of pore pressure in the surrounding soils undergoing compaction. The low mobile compaction grout with high internal friction and /or cohesion could prevent hydrofracture of the dam core, migration of grout material to undesirable areas such as the filter zone of the dam, or unexpected heave of the crest or slope of the dam. The proper grouting pressure, flow rate, and volume were selected for best grouting effect at a given hole or area through trial and error examination of compaction grouting (Korea Water Resources Corporation, 2000; Lim et al., 2004). The soft saturated zones which are probable damaged areas resulting in the leakages were encountered below water during drilling of compaction grouting holes or the dam core. 5% cement by weight was added into the grout injected into the soft loose zone in order to strengthen the grouted soil. To prevent hydro fracturing, polymer textile was added in the injecting material for grouting. The compaction grouting work was controlled for the effective grouting application to damaged zone. The relationships between tip pressure of compaction grouting and depth of ground were analyzed, then the criteria for the best application of compaction grouting work were given in Figure 2 (Denver Korea Grouting Co. et al., 2000; Lim et al., 2004). The application of tip pressure and grout volume with depth in this site was plotted in Figure 3 for comparing the primary hole 10-1-C and the secondary hole 10-1-E (Denver Korea Grouting Co. et al., 2000; Lim et al., 2004). The grouting tip pressure of the primary hole 10-1-C was low pressure indicating an existence of void and loose zone. On the other hand the grouting tip pressure of the secondary hole 10-1-E was high pressure above those required for the closure criteria indicating a hardening of void and loose zone by primary grouting.

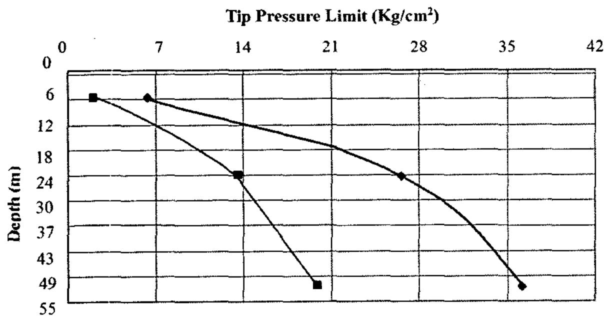



Fig. 2. Compaction grouting tip pressure and volume criteria

Based on the logging data for the actual injected pressure and dosage, the core condition prior to the grouting activity was implied. The compaction grouting for the weakest regions was conducted at Sta. No. 10 and Sta. No. 12 from May 18 to August 24, 2000 (Korea Water Resources Corporation, 2000; Lim et al., 2004). A dry drilling method for the best application of compaction grouting was used. The compaction grouting was conducted in advance for every 0.3m from the bottom of excavation. It was reported that the grouting activity continued until the designed injection pressure-dosage. The injection pressure and slurry amount were automatically measured and recorded. It was speculated that the point in which a large amount of slurry was injected would be loose; it thus means the risky points in terms of stability. The grouting injection analysis on the pressure and dosage was intensively conducted through many sections of the dam core. Figure 4 demonstrates the order of drilling borehole and grouting works to confirm the grouting effects. The compaction grouting was applied at the distance of 80 m around Sta. No.10 and 12 as shown in Figure 4. The number means the order of compaction grouting works and the unit of cubic cm ($cm^3$) at the lower figure means the injected grouting volume.

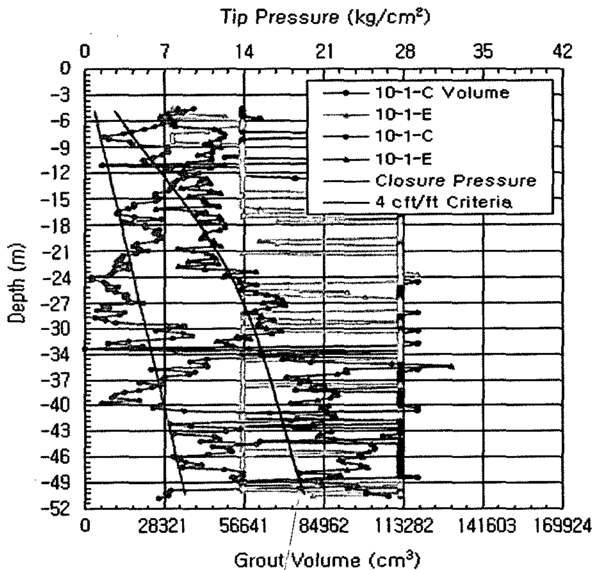



Fig. 3. Pressure and volume of compaction grouting

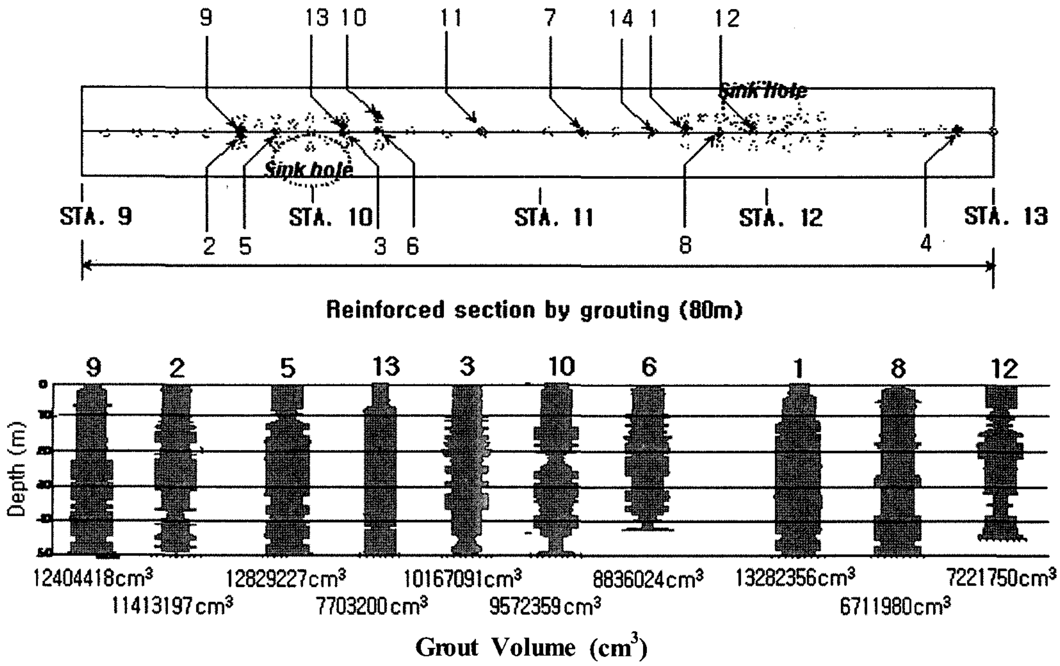



Fig. 4. The order and volume of compaction grouting works

Figure 5 presents the injected amount results through the dam axial section and the depth with repaired distance of 80 m. In the contours, it can be known that a large amount of grouts was injected at 20~30 m distance around Sta. No. 10 and Sta. No. 12. Namely, it seems that there was a possible symptom of relatively loose condition before remedial work in this section. This figure shows the distribution of dam core injection amount by depth and the station where it was reinforced near Sta. No. 10 and Sta. No. 12 preponderantly is indicated with dotted line square. The regions of loose state resulted in transporting of the injected grouting slurry that is recognized by the injected slurry with a pigment.

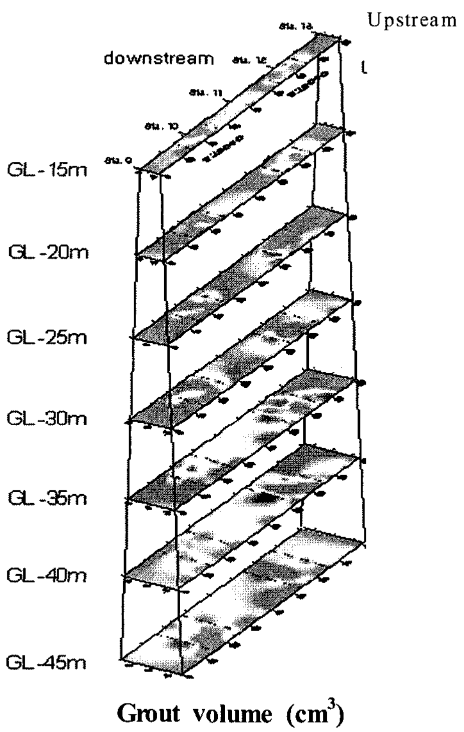



Fig. 5. Injection of the compaction grouting

Figure 6 presents the borehole location for precise safety diagnosis and confirmative investigation (Korea Water Resources Corporation, 2000; Lim et al., 2004). At the region repaired by the compaction grouting, the four boreholes were drilled for the detail investigation and three boreholes were drilled for the confirmation of the grouting. In-situ and laboratory experiment were conducted through the borehole to determine pore pressure, permeability, N value, water content, liquid and plastic limit, etc. and the V-notch to determine leakage and seepage through dam body. V-notch was used as a weir installed at downstream to determine discharge and flowrate. In addition, geophysical survey was performed at crest and downstream of the dam. The measuring device was installed at Sta. No. 9 to 13. To investigate

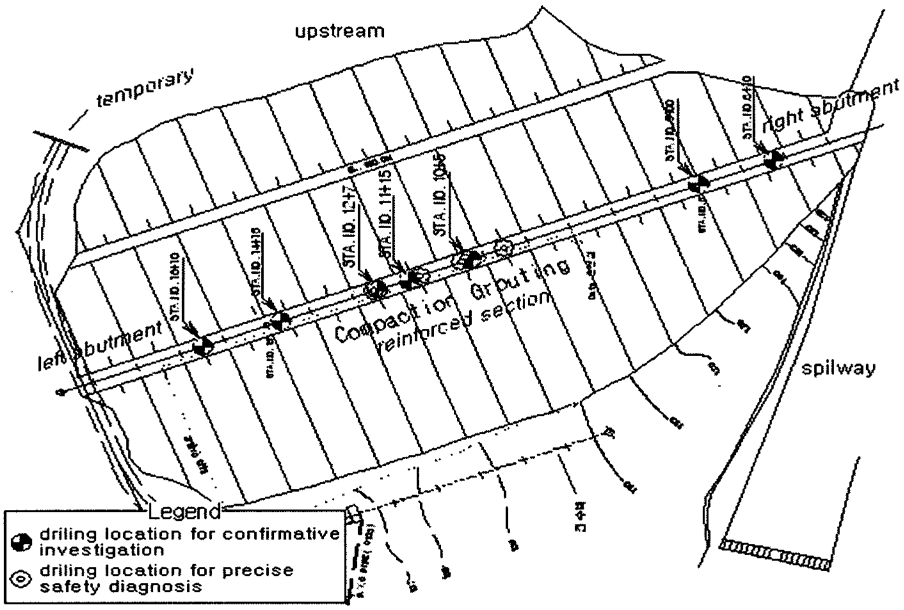



Fig. 6. The investigation drilling location which enforced in precise safety diagnosis and confirmative investigation

the remediation effects on the damaged core zone, the injection materials were sampled at the site (D-2) where originally the core materials were existed.

## 3. Results and Discussion

### 3.1 Leakage

#### 3.1.1 Leakage and Water Level

The dam construction was completed in July 1993. The leakage detection devices were installed in December 1997. The leakage was firstly detected in February, 1998 (Korea Water Resources Corporation, 2000; Lim et al., 2004). The average leakage before the grouting indicated about 3,240 ton/day at maximum reservoir water level. Figure 7 shows reservoir water level, rainfall and leakage change with time. The reservoir water level and leakage increased through heavy rainfall seasons and decreased through light rainfall seasons. But it was revealed that there was no significant increase of leakage after grouting application in June, 2000.

The leakage through the dam was measured and analyzed in order to evaluate compaction grouting effect during the remedial work. Figure 8 presents the reservoir water level and leakage change during the repairing periods by compacting grouting. The compaction grouting

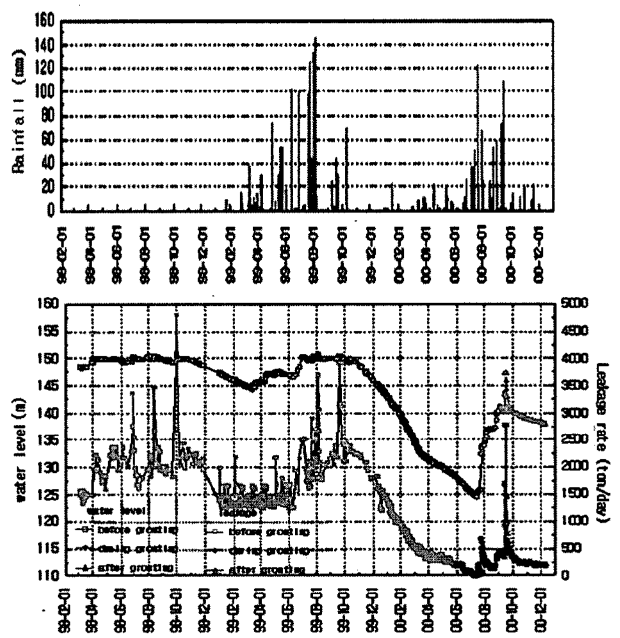



Fig. 7. Changing patterns on water level-leakage-rainfall with time

initiated on June 16, 2000. The leakage was significantly reduced as shown in this figure 8. The leakage increase on July 16 and 23, 2000 resulted from the heavy rainfall of the dam areas. Although the reservoir water level increased, the leakage tended to decrease. Figure 9 demonstrates leakage reduction during the compaction grouting works. The compaction grouting effectively worked against the leakage through the dam. The areas around Sta. No. 10 and 12 were the weakest regions in this earth fill dam. The leakage decreased to approximately 300 ton/day after the remedial work as well. This leakage of 300 ton/day after the remedial work corresponds to about 10 percents of the maximum leakage of 3,240 ton/day before the remedial work.

As shown in Figure 7, the leakage substantially increased after the completion of dam construction and during dam operation before the remedial work. Furthermore, it was observed that the leakage significantly increased when the reservoir water level was higher than 145 m. It is possible that rainfall and poor dam materials can cause the leakage increase. However, the detected leakage was not significantly dependent on rainfall events as shown in Figure 10. Figure 10 shows the relationships between leakage and water level which eliminated the record during 5 days after rainfall. The repression line can be expressed as y = 10.433 Ln(x) + 69.467 ($R^2$ = 0.9147). Figure 11 represents the correlations of leakage − water level with low water level and high water level. The values of measured leakage did not show great difference one another and over allowable leakage in the cases of water level rise and water level drop. Thus, the difference of water level does not significantly affect on the rapid increase of leakage rate.

Seepage through the dam was simulated using SEEP/W developed by Geo-Slope Co., Canada to investigate whether influx water 3,000 ton/day can seep through the dam or not. As a result of seepage analysis, the estimated seepage value was 807 ton/day at reservoir water level of 138.5 m that was similar to measured leakage at down stream of the dam. The calculated permeability was

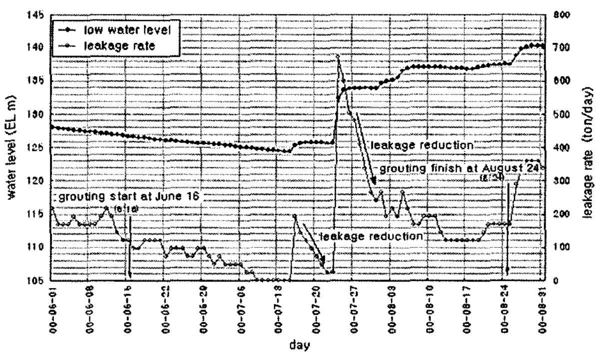



Fig. 8. The reservoir and leakage change during grouting

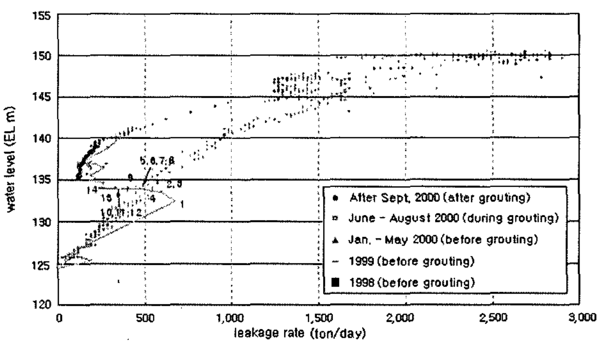



Fig. 9. Leakage reduction during the grouting activity

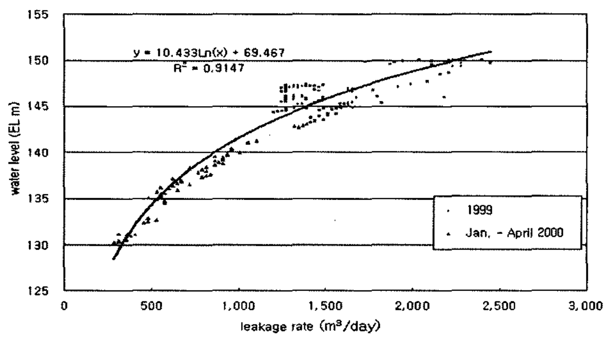
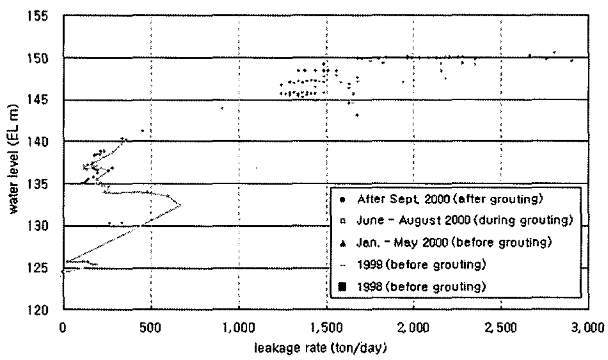
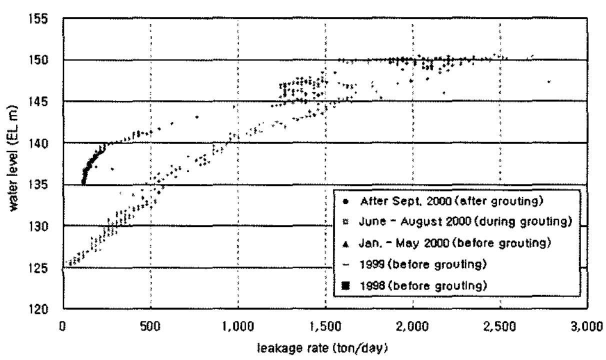



Fig. 10. Relationships of water −leakage (eliminated the record during 5 days after rainfall)




(a) water level rise




(b) water level drop

Fig. 11. The relationships between water level and leakage quantity with water level rise and drop

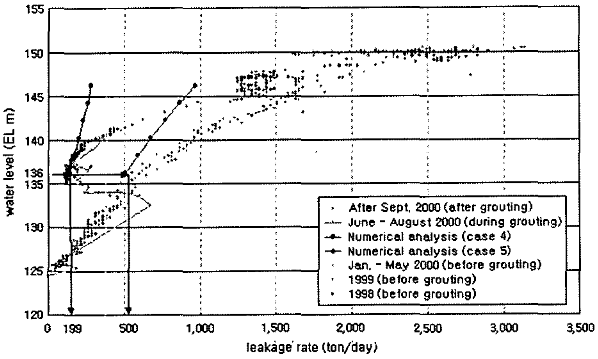



Fig. 12. Comparison of water level and leakage amount (simulated result versus measured result)

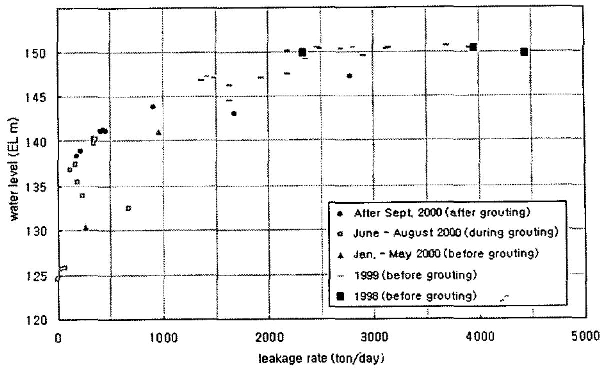
$1.1\times10^{-4}$ cm/sec which was not appropriate as core material in an earth fill dam. The measured leakage through dam body is greatly higher than the simulated leakage using SEEP/W software by comparing seepage analysis result with measured result during grouting works as shown in Figure 12. Therefore, it is known that the poor dam body alone did not cause the measured leakage. There should be water influx from another pathway.

### 3.1.2 Leakage and Rainfall Intensity

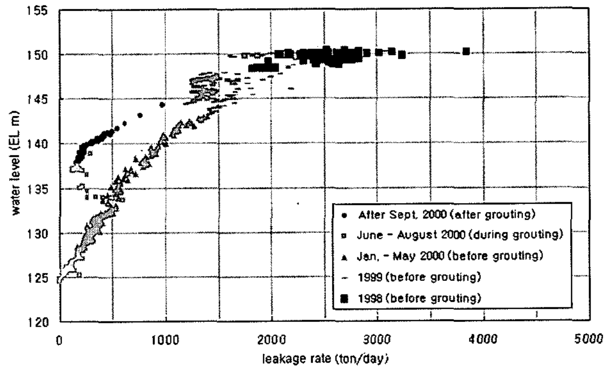
Figure 13 demonstrates the relationships between water level and leakage with rainfall intensity difference of 20 mm over and below. The values measured leakage do not show great difference one another and over the allowable leakage in the case of rainfall over 20 mm and rainfall below 20 mm. Thus, it can be suggested that the difference of rainfall does not have significant effect on the rapid increase of leakage rate.

## 3.2 Pore Pressure

When the compaction grouting was performed, piezometers were installed at Sta. No. 10 and Sta. No. 12. The three piezometers were installed at each measuring point as shown in Figure 14 and Figure 15. The pore pressure was automatically measured and recorded with the injection pressure and dosage. Table 2 shows the pore pressure measuring location, grouting date, dosage and reservoir water level. The measured pore pressures of the borehole at Sta. No. 10 and Sta. No. 12 were illustrated in Figure




(a) rainfall over 20 mm/hr




(b) rainfall below 20 mm/hr

Fig. 13. The relationships between water level and leakage considering rainfall over and below 20 mm/hr

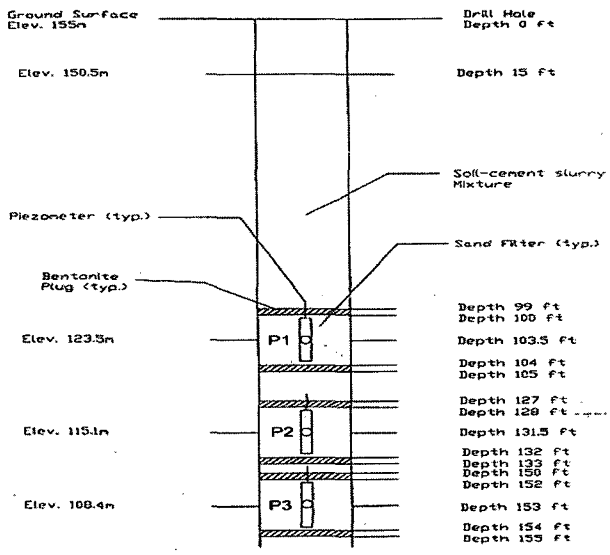



Fig. 14. Pore pressure instrumentation

16 and Figure 17.

The pore pressure measured at EL. 108.4 m significantly increased due to the grouting pressure. The compacting grouting broadly influenced on the dam and caused an increase in the pore pressure. The pore pressure significantly increased from 2.4 $kg/cm^2$ to 16 $kg/cm^2$ due

Table 2. Outline of pore pressure measuring location and grouting conditions

| Pore pressure measuring location | Analysis objective grout hole | Grout injected date (Year 2000) | Injected quantity ($m^3$) | Low water level during injection (EL. m) |
|---|---|---|---|---|
| Sta. No.10 | 9-6d | July 4 | 2.718 | 125.25 |
| | 10-3a | July 6 | 2.549 | 125.10 |
| | 9-1b | August 15 ~16 | 11.100 | 136.92 |
| Sta. No.12 | 12-3a | July 7 | 2.973 | 124.96 |
| | 11-5a | July 8 | 1.926 | 124.87 |
| | 13-1b | August 7~8 | 13.705 | 137.05 |

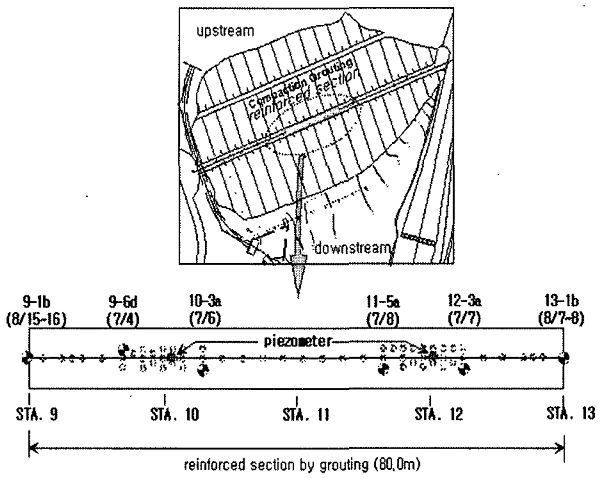



Fig. 15. Laying location of pore pressure instrument and location of grouting hole

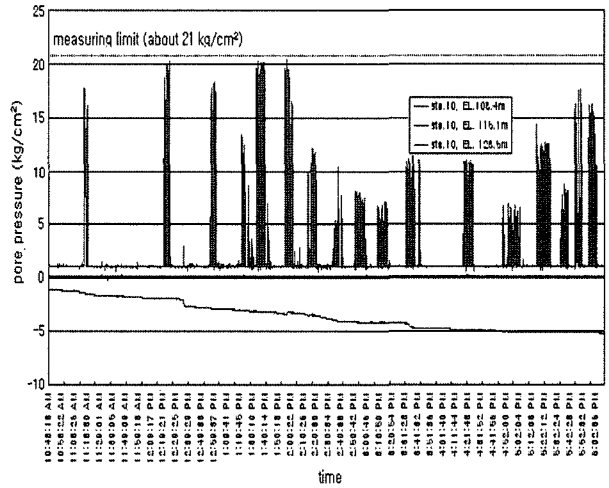



Fig. 16. Pore pressure change of 9-6d point during grout injection (July 4th 2000, low water level (125.25 m)

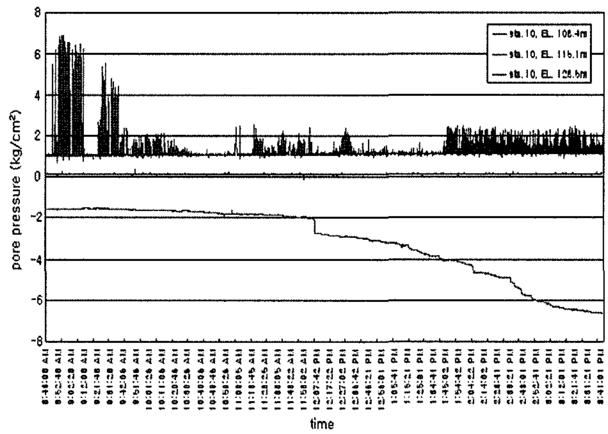



Fig. 17. Pore pressure change of 10-3a point during grout change (July 6th 2000, low water level 125.10 m)

to the influence of grouting pressure. Particularly, the pore pressure increased at borehole 9-6d to 21 kg/cm$^2$ which is the limit of the pore pressure device. It was considered that the increment of pore pressure could affect the deformation of dam, but this phenomena did not affect the development of dam deformation by measuring data of dam deformation. Thus, the pore pressure measured at high and middle elevation in dam did not increase due to grouting pressure dissipation, but the pore pressure measured at low elevation in dam increased due to grouting pressure confinement.

In this way the loadbed on the partially or fully saturated soil may generate excessive pore water pressure in internal core, and cause a significant change in ground and dynamic characteristic such as liquification of reservoir water. This greatly affects compression ratio by reducing effective stress and shear strength, which cause consolidation and settlement. Therefore, accurate measurement and analysis of pore water pressure are very important for dam safety.

## 3.3 Permeability

### 3.3.1 Permeability Before Grouting

According to the in-situ monitoring, a large amount of water influx to the borehole appeared at around 20 and 40 m deep. The high permeability regions appeared at 20 m and 35 m deep according to the predicted permeability distribution before the grouting work. As a result of the investigation, seepage would occur in the certain potion of the core. The in-situ water content and plasticity at the point with influx water was higher than the point in which there was not any water influx. The plastic index (PI) was slightly higher than the PI value of 10. Based on the Unified Soil Classification System (USCS), most of the core materials were classified as SC and CL soils. The GC soils were recognized at depth 30 to 40 m. The in-situ permeability tests based on a recovery method were conducted through the water influx areas of the dams (Korea Infrastructure Safety and Technology Corporation, 2005). Figure 18 shows that in-situ permeability of the dam core materials before the compaction grouting. This figure represents the range of in-situ permeability of $10^{-4} \sim 10^{-6}$ cm/sec and the average in-situ permeability of $10^{-5}$ cm/sec.

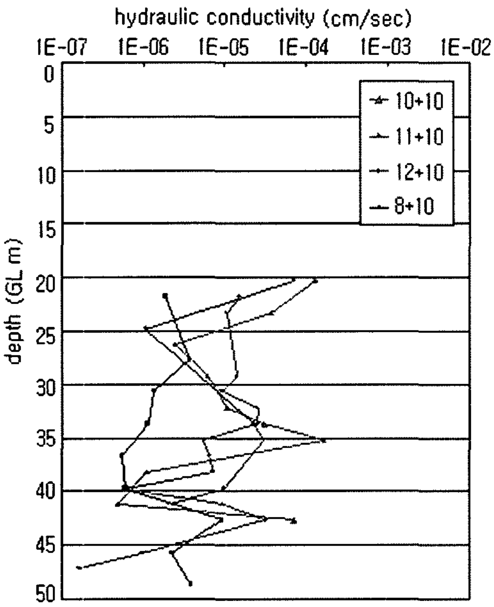



Fig. 18. In-situ permeability of dam core before the grouting activity

Table 3. The permeability determined by laboratory falling head test

| Sta. No. (depth) | Hydraulic conductivity (cm/sec) |
|---|---|
| 9+10 (12.0 m) | 3.00E-06 |
| 10+10 (13.0 m) | 7.38E-07 |
| 10+10 (43.5 m) | 5.12E-06 |
| 11+10 (12.0 m) | 4.03E-06 |
| 11+10 (45.0 m) | 5.78E-06 |
| 12+10 (13.5 m) | 2.76E-06 |

The laboratory falling head test was carried out using core specimen. The permeability determined by a laboratory falling head test ranged from 7.38 X $10^{-7}$ cm/sec to 5.78 X $10^{-6}$ cm/sec as shown in Table 3. The required permeability for a core material in an earth dam was 9.71 X $10^{-7}$ cm/sec. It was speculated that the permeability of the core material increased to about ten orders of magnitude before the remedial work. However, with the consideration on several reasons that were not reflected in an actual test such as weak seam, it was possible that the permeability of the whole core material would be higher than those actually measured.

### 3.3.2 Permeability After Grouting

Figure 19 shows that in-situ permeability of the dam core materials after the compaction grouting. This figure represents that the range of in-situ permeability is $10^{-5} \sim 10^{-7}$ cm/sec and the average in-situ permeability is $10^{-6}$ cm/sec. In comparison with permeability prior to the remedial activity, the measured in-situ permeability after the compaction grouting decreased to 10 orders of magnitude. However, groundwater level significantly increased to 14 m after water influx around 35 m during drilling the borehole of Sta. No. 11+15 in spite of conducting a recovery test. Therefore, it was speculated

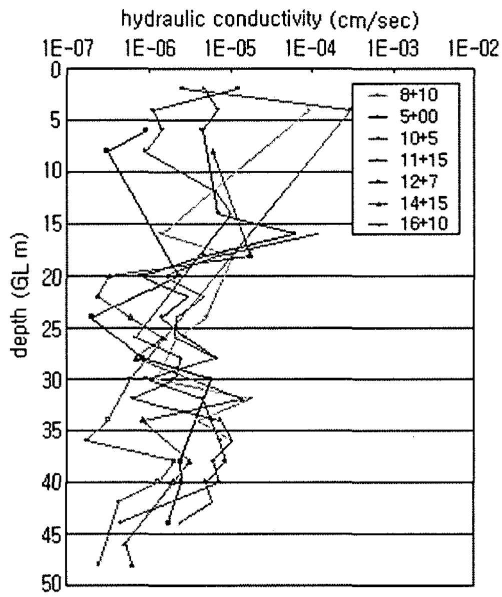



Fig. 19. In-situ permeability of dam core after the grouting activity

that seepage through the high permeable areas within the dam might exists through the dam core.

## 4. Conclusions

Compaction grouting method was applied to repair and remediate for reduction of leakage from the damaged core at earth fill dam. In-situ and laboratory experiment for earth fill dam were conducted to determine leakage, pore pressure, and permeability before, during and after the remedial works. We could get the following conclusions from the above mentioned compaction grouting evaluation and assessment.

(1) The leakage after the compaction grouting to the damaged dam core decreased to approximately 10 percents of the maximum leakage before the compaction grouting.
(2) The pore pressure within dam core slightly increased due to influence of grouting pressure, but not affected the further development of dam deformation.
(3) In comparison with in-situ permeability prior to the remedial activity, the measured in-situ permeability decreased to 10 orders of magnitude after the compaction grouting.
(4) The compaction grouting effectively worked as a alternative remedial works against the leakage through the dam core.

## Acknowledgements

This paper was written based on data and information taken from KOWACO and Sambu Construction Company in Korea. The authors give their sincere gratitude to the staff and engineer of the KOWACO and Sambu Construction Company for their cooperation and support.

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(received on Jan. 13, 2006, accepted on Oct. 30, 2006)