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Doctoral Dissertation

RESEARCH ON STRUCTURAL AND ECONOMIC OPTIMUM DESIGN METHOD OF INCLINED-TYPE CORE STRCUTURE FOR HEIGHTENING FILL-TYPE DAM

貯水池ダムの嵩上げのための傾斜型コア構造の
構造的および経済的最適化に関する研究

Young-hak Lee

July, 2015

Graduate School of Engineering

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Abstract

The study provides a research on structural and economic optimum design method of inclined-type structural core (structural core: structure combined with an existing core and a new one whose permeability and/or width are conditioned relatively) for heightening fill-type dam. Specifically, a concept of the expanded structural core construction method in the core heightened dam by inclined-type was proposed as the solution to guarantee the structural safety for core heightening work of the existing dam, and it evaluated the effects of the expanded structural core by using FEM analysis on seepage characteristics and dynamic performance, as means to reinforce the core joint which can be vulnerable to permeable and seismic behaviors. In connection to the reinforcement method for the core joint, this study suggested the four kinds of the scale of the core expanded from the core joint. Hereupon, an optimum scale of the expanded structural cores that can be economic in the long run, considering the structural reinforcement effects were discussed. The specific details for the proposed expanded structural core construction method outlined in chapter 1, the main issues in each chapter are outlined as follows.

In chapter 1, general background and objectives were presented. The dam heightening construction for securing water resources and prevention of disasters such as flood and droughts in relation to climate change has been performed by using an existing fill-type dam which was constructed in upper part of an existing vertical core-type. In regard to this, this study has paid attention to a core heightened dam by inclined-type in various construction methods for dam heightening work, due to the shape of the structural core (tilted structure) which can be vulnerable to permeable and seismic behaviors. In this tilted structural core, the possibility of damage during earthquake is expected to be high at the core joint due to the core deformation caused by the concentration stress in the position (core joint) where the shape of the core is changed. In addition, the core damaged by an earthquake is closely associated with the permeable problems like water leak (piping) regarding the dam safety, and thus it can cause an the treatment cost related to repair and/or reinforcement resulting from an increase of the leakage in the downslope slope. On the top of that, since the existing and the heightened cores (new core) have different ranges of strength and permeability despite having the same material, the zone of the structural core should be carefully deal with.

In this study, accordingly, an expanded structural core construction method as a kind of core reinforcement in the core heightened dam by inclined-type was proposed and evaluated on permeable and seismic behaviors as the core is the most important structure to keep the safety of the dam.

In chapter 2, based on the above, the effects of the expanded structural core on seepage characteristics by using FEM seepage flow analysis were discussed. First, the possibility of piping the core heightened dam by inclined-type was evaluated into seepage quantity and hydraulic gradient. Hereupon, the flow velocity at the core joints and the seepage quantity through the newly heightened core (inclined-type) were considered. Second, the residual effect of saturation of the core under the conditions of water-level drawdown with regard to the dry season was evaluated. Last, this study proposed the available coefficient of permeability of the heightened core (new core) that can be applicable to the heightening work as means of enhancing the work efficiency with the rational cost and the construct abilities. The results investigated in this chapter are outlined as follows.

In the piping inspection, piping on the downstream slope revealed that the risk of core expansion-induced piping is extremely low. In addition, seepage problems of the core joint can be control by the expanded core joint structure owing to the large decrease in the quantity of seepage passing through the heightened core and the flow velocity at the core joint.

In addition, the zone of the saturation degree of the heightened core under water drawdown was found to be increased as the moisture-retaining zone increased in proportion to the expanded scale of the structural core, and thus possible damages induced by core deformation and cracks can be reduced. On the basis of the results, the expanded structural core is expected to have a structural reinforcement on the zone of the core joint in a stable state than that of the pre-expansion core in points of view on permeable behavior. Meanwhile, the range of available coefficient of permeability for heightened core (k_{new}: new core) investigated in this study can be somewhat alleviated than that of the design coefficient of permeability, and thus it is expected to improve the heightening work efficiency within allowable seepage quantity as the area of the borrow pit around the reservoir available for core construction is wide.

In chapter 3, the effects of the expanded structural core on seismic performance by using FEM dynamic response analysis were discussed. First, the natural periods of the heightened dam was investigated to understand the impacts on the expanded scale of the structural cores to the core heightened dam. Hereupon, the dynamic behavior (distribution of the shear stress) on the heightened core by inclined-type was evaluated by input sinusoidal waveform to understand the deformation due to the core shape, and it focuses on the shear stress that occur in the core joint zone. Second, the shear stress acting on the expanded scale of the structural core was evaluated by input seismic motions based on the result obtained from the input sinusoidal wave. The results are outlined as follows.

In the natural period analysis, it appeared that all scales of the expanded structural core have the same periods (0.16 s), and thus it is expected that expanded structural core investigated in this study will not be affected to the core heightened dam by inclined-type. In the input sinusoidal wave, the shear stress acting on the heightened core by inclined-type was found to be deformed easily at time in the response for downstream-side direction compared to the response for upstream-side direction. In input seismic motions, the shear stress that occur in the core joint zone was reduced gradually as the expanded scale of the structural core increased, and thus the expanded structural core construction method proposed in this study is effective in terms to prevent the core deformation and/or cracks in the core joint.

In chapter 4, an optimum structural core through the economic analysis based on the results obtained in the seepage flow analysis and dynamic response analysis are suggested and discussed. The largest scale of the expanded structural core in this study has the biggest structural reinforcement but the construction cost increased. Thus, the optimum scale of the expanded structural core was determined based on the assessment whether the expanded structural core has an economic in relation to the future water value. To present the optimum scale of the structural core in economic perspectives, it was evaluated by Objective Life Cycle Cost (OLCC) which was proposed in this paper, based on the concept from Life Cycle Cost (LCC). The OLCC was defined as the sum of the Objective Initial Construction Cost (OICC) and Objective Loss Cost (OLC: leakage loss cost as one kind of Running Cost) during the life cycle of the dam. Especially, this study applied that the estimation of OLC was considered based on the compound interest concept which was applied with the fluctuation of water value in relation to the future climate change according to the time of years. The results are outlined as follows.

The optimum scale of the expanded structural core evaluated by objective life cycle cost (OLCC) was changed by the price of water, and it is effective economically as it can minimize the sum of the construction cost and the leakage water price of future heightening work. Hereupon, it is expected to be economically payable as a means of reduction of the water leakage considering the rise in the value of water in the future, and the expanded structural core having an optimal configuration within rational construction cost can be established.

From the result, since awareness of climate change and its implications for water security in the global society is growing, the core heightening work would be important over time. In regard to this, the proposed models in this study can contribute to the stabilization of the core heightened dam in the long run, in terms of economic optimization as well as the optimum configuration for the structural safety.

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July, 2015

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CONTENT

Definitions of Terms

For understanding the meanings of this paper, the typical terms are identified as follows in this paper.

Bank adding heightened dam- A heightened dam where a new earth bank with a core is added at the downstream side

Core: An internal structure in the body of a fill-type dam made with fine soils to prevent leakage

Core heightened dam- A heightened dam adding new core to old core for a fill-type dam

Structural core- A structure combined with an existing core and a new one whose permeability and/or width are conditioned relatively

Expanded Structural Cores- A core structure where an adding new core is expanded to strengthen the joint between an old core and a new core

Economic optimum design method- A design method to consider the optimum conditions economically

Expanded structural core construction method- A construction method for the core heightened dam to expand the core joint between an old core and a new core

Heightened dam- A renewal dam whose height is higher than the existing dam to increase the water storage capacity

Inclined core heightened dam- A heightened dam adding a new core to an old core inclined in a fill-type dam

Initial construction cost- A cost to construct a structure initially

Leakage loss- A loss induced by leakage to maintain a fill-type dam during life time, which is assumed a minus benefit in this paper

Leakage loss cost- A price of water leaked during life time of the objective dam

Life cycle cost- A total sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a structure, or system. In includes running cost (repair or reinforce work), installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life

Minus benefit- A leakage water price is the minus benefit which is considered as the leakage water price in this study

Newly constructing heightened dam- A heightened dam which is a new fill-type dam higher than the existing dam and constructed at the downstream site close to the existing dam

Optimum design method- A design method to consider the optimum conditions structurally and economically

Objective initial construction cost- A partial cost of a total initial cost to discuss the specific purpose, for example, an initial construction cost relating to expansion of core in this paper

Objective loss cost- A loss cost to relating to the specific purpose, for example, a leakage loss cost in this paper

Objective running cost- A partial running cost of a total running cost to discuss the specific purpose, for example, a running cost relating to the structural core in this paper where a maintenance cost and minus loss cost are included

Reservoir dam- A kind of a fill-type dam to store water for agriculture

Structural optimum design method- A design method to consider the optimum conditions structurally

Vertical core heightened dam- A heightened dam adding a new core to an old core in a fill-type dam vertically

Water price- A water price to estimate the water cost of leakage water from a fill-type dam

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Chapter 1

INTRODUCTION

1.1 Background

Recently, large fluctuations in annual precipitation have caused severe floods and droughts due to rapid climate change, requiring many countries to cope with extensive natural disaster damage and future water security. In regard to the South Korea, the rainfall patterns are very variable as shown in Figure 1.1, it's been endowed with an environment wherein it is difficult to manage water. In addition, as the month of concentrated seasonal precipitation due to the rapid climate change is moving from June to July, the shortage of agricultural water is expected in June when most of the water is required for agricultural purposes[1)].

In connection to this environment condition, 89 % of reservoirs[2)] are small-scale dams with less than 100,000 m^3 of available reservoir storage as shown in Figure 1.2 as examples in South Korea; hence enough supply of water is difficult, the polarization between droughts and rainfall patterns also gets severe, and expansion of various ways of supplying water for agricultural use is unavoidable; accordingly when all of these are taken into consideration, plans for securing water resources and prevention of disasters are required all the more.

On the top of that, most of the reservoir dams are made in the form of fill-type dam which occupies about 68% of the older dams[2)] constructed over 50 years ago, as shown in Figure 1.3. In regard to the older dams, it can have a safety of the reservoir dams since a leakage paths inside the dam body may exist due to the change of water level of reservoirs and rainfalls for a long period of time. Specifically, if there were structural accident and weaknesses in the dam body, the soil structure is likely to be failed since soil materials can enter through the leakage paths which were already formed.

Based on the above details, reservoir dam heightening projects are planned and performing across South Korea; 110 agricultural reservoir dams are being heightened[1)].

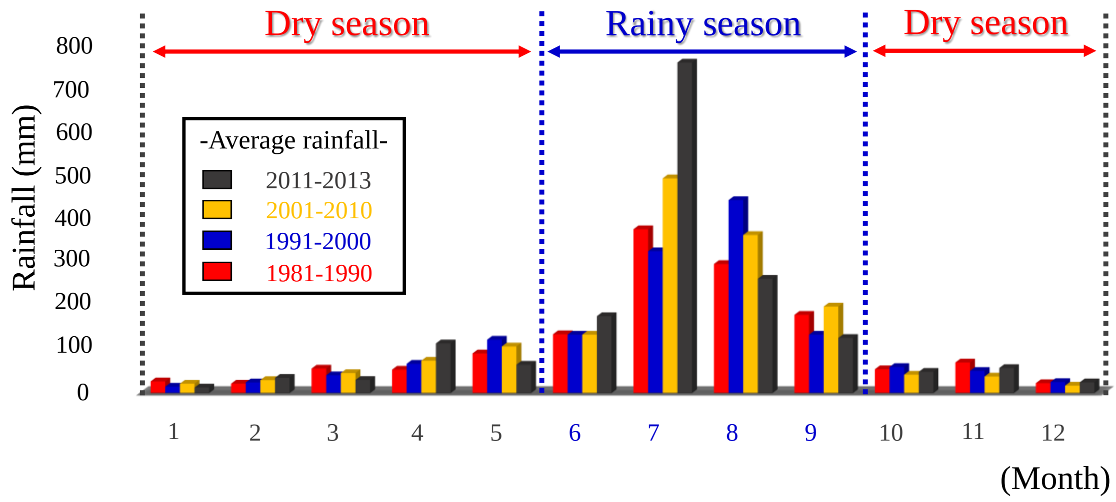


Figure 1.1 Rainfall characteristics of South Korea in 2013

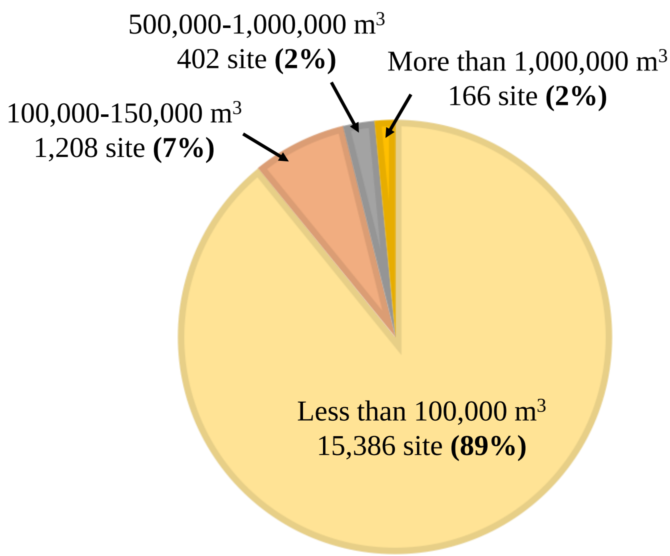


Figure 1.2 Reservoir storage capacity of Korea in 2012

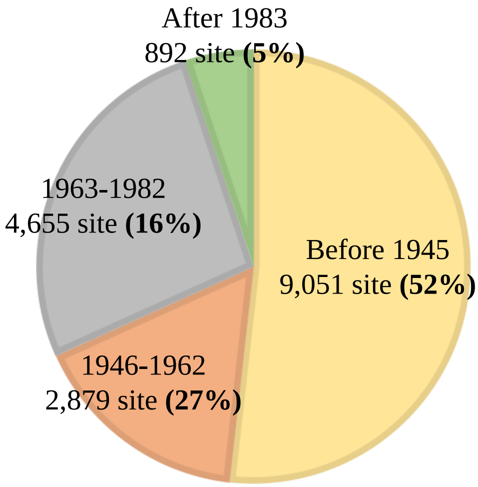


Figure 1.3 Number of reservoir dam sites classified by construction years in 2012

1.2 Classification for Heightening Method and Types

Here, most reservoir dams are made in the form of zoned-fill dam (Core zone: clay and silt, Embankment zone: silt and sand, Filter zone: sand) with cores installed inside; the heightening methods are decided after considering topographic position, rainfall patterns, frequency of accidents etc., as an examples in South Kores, and Table 1.1 presents the characteristics consideration of the fill-type dam to decide the heightening construction method and types[4)]. Figure 1.4 shows the conceptual figures of the heightening method for the three types which are the core extension of existing dam (core heightened dam), the new core construction in backside of existing dam and the new dam construction that is moved toward downstream to secure the water resource all the more. Here, the core heightened dam can further be divided into two types as an inclined core and a vertical core heightened in upper part of existing core as shown in Figure 1.4. Figure 1.5 shows the statics[1)] of number of the heightening site (total 110 sites) according to the construction method, and more than half of number of the heightening site has been adopted in the core heightened dam by inclined or vertical types. Here, the reason to use the core heightening method is that it have an advantages that can be minimized from an economical and environmental standpoint more than new dam construction. In addition, one characteristic of core heightening method is it is available water for irrigation even construction periods.

Table 1.1 Classification characteristic according to heightening methods Revised Ref.4)

Division	Core heightened dam	New core construction in backside of existing dam	New dam construction
Planning height	0-5m	5-15m	More than 15m
Increased water volume	Water increased in low height of core extension (heightening dam nearby water supply area)	Water increased in new core construction (heightening dam little far from water supply area)	Much water required (enough space for spillway construction required) (new dam located in downstream side more than existing dam
Possibility of leakage	Possible in the joint zone between dam body and existing spillway	Possible (new core constructed in existing dam backside)	Less possible (new core constructed)
Repair and Reinforcement	Little complicated (inclined-core) Simple (vertical-core)	Simple (vertical core)	Simple (vertical core)
Construction cost	Good (inexpensive)	A little good (expensive)	Poor (most expensive)

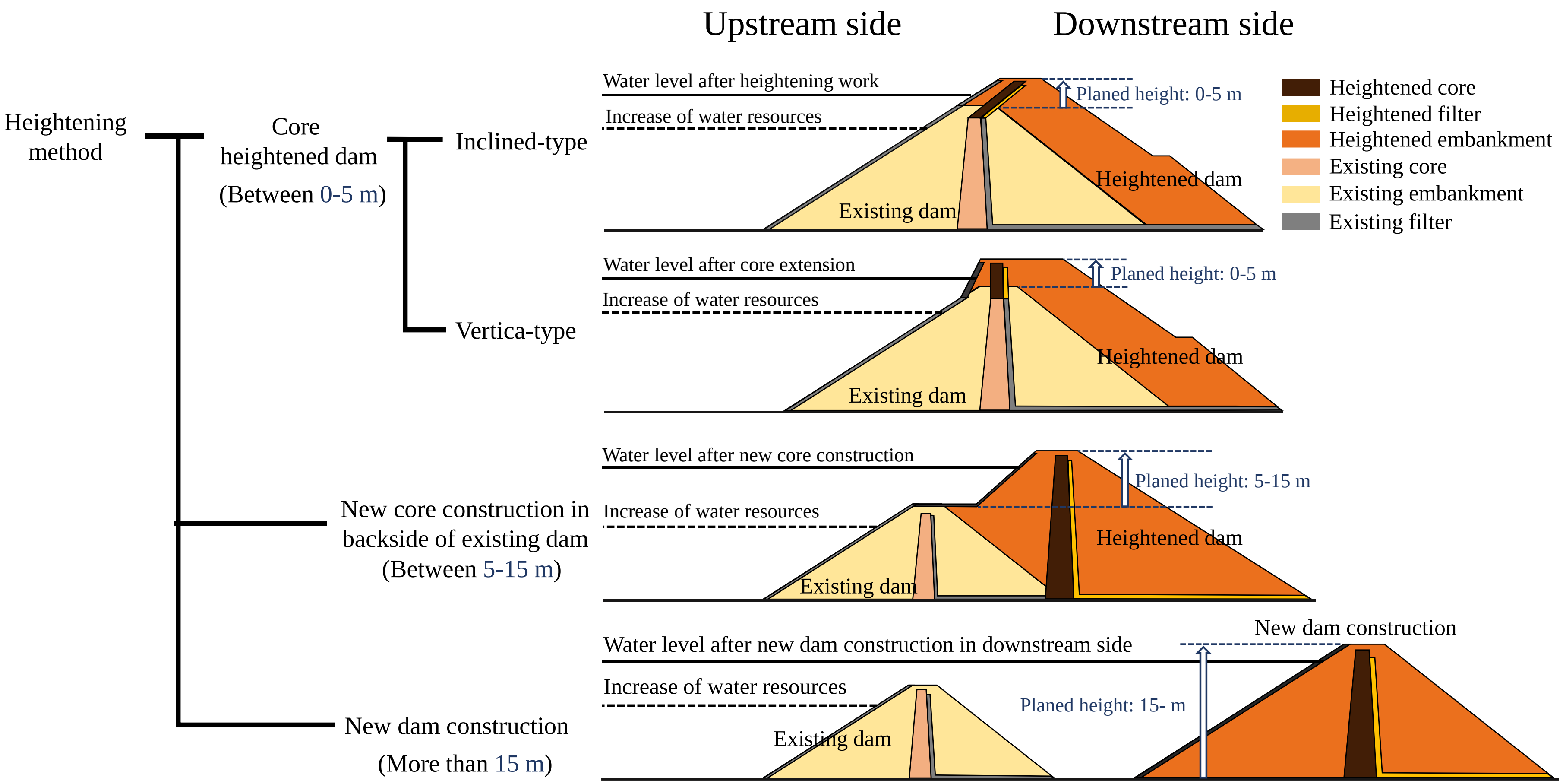


Figure 1.4 Conceptual figures of the heightening methods

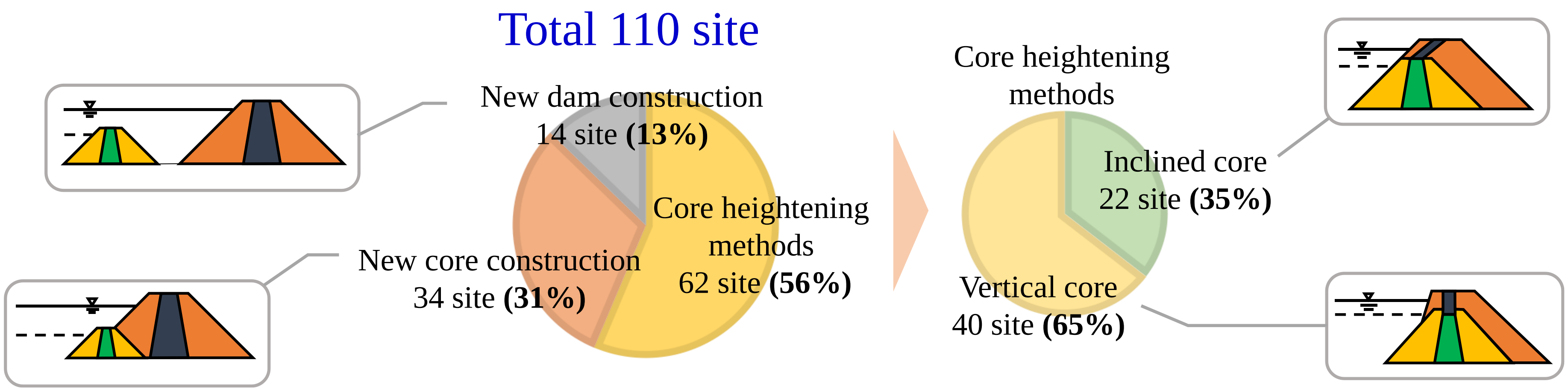


Figure 1.5 Number of the construction site (total 110 site) according to the heightening methods

1.3 Past Failure and Failure Mode in Fill-Type Dam

This section contains general past failure and failure mode in fill-type dam, and its failure mode in conjunction with the stability of the core heightened dam on this research, was described about how it affects.

Table 1.2 shows the overall failure statistics in fill-type dams presented by Foster et al (2000) [5]. The major causes for dam failure and accident can be explained by piping and overtopping, and it has a large proportion of the dam disasters. Based on the failure statics, the piping that passes the dam body revealed about 43.2% of the ratio, about 44.6% in overtopping and appurtenant. Here, the piping that passes the dam body may be more hazardous higher than that of overtopping since the condition for occurrence of dam failure and accident are different; in general, the overtopping was caused by the external conditions such as rainfall variability or flood, but the piping was influenced by internal conditions such as soil erosion due to the deterioration of structures by elapsed time and structural failure inside of embankment like material cracks. Here, since almost of the soil structures such as the reservoir dams are inhomogeneous and water is constantly flowing, the structural problem caused by the internal conditions (i.e. erosion and cracks, etc.) should be dealt with all the more.

As described the above, since the piping patterns and causes are varied and complex, it is important to understand the piping mechanism and the possible risks. Benjamin and Cornell (1970), McCormick (1981), Pate-Cornell (1984), Ang and Tang (1975, 1990) and Henley and

Table 1.2 Overall failure statistics in fill type dams up to 1986, excluding dams constructed in Japan pre-1930 and in China [Revised Ref. 5)]

Mode of failure		Number of cases in each failure
Overtopping and appurtenant	Overtopping	46
	Spillway–gate	16
Piping	Through embankment	39
	Through foundation	19
	From embankment into foundation	2
Slides	Downstream	6
	Upstream	1
Earthquake–liquefaction		2
Unknown mode		8
Total number of failures		139

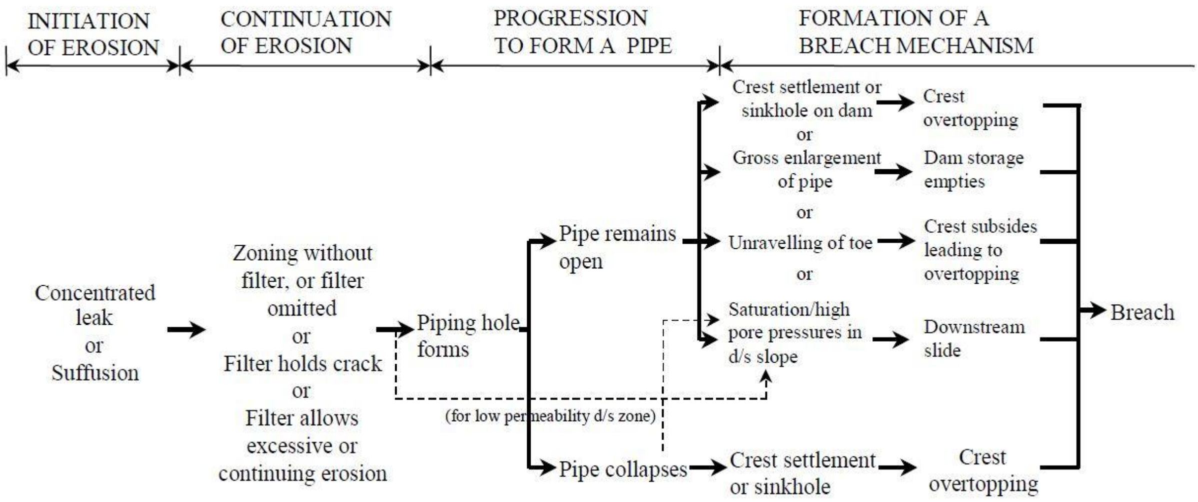


Figure 1.6 Advanced failure path diagram for failure by piping through the embankment[6)]

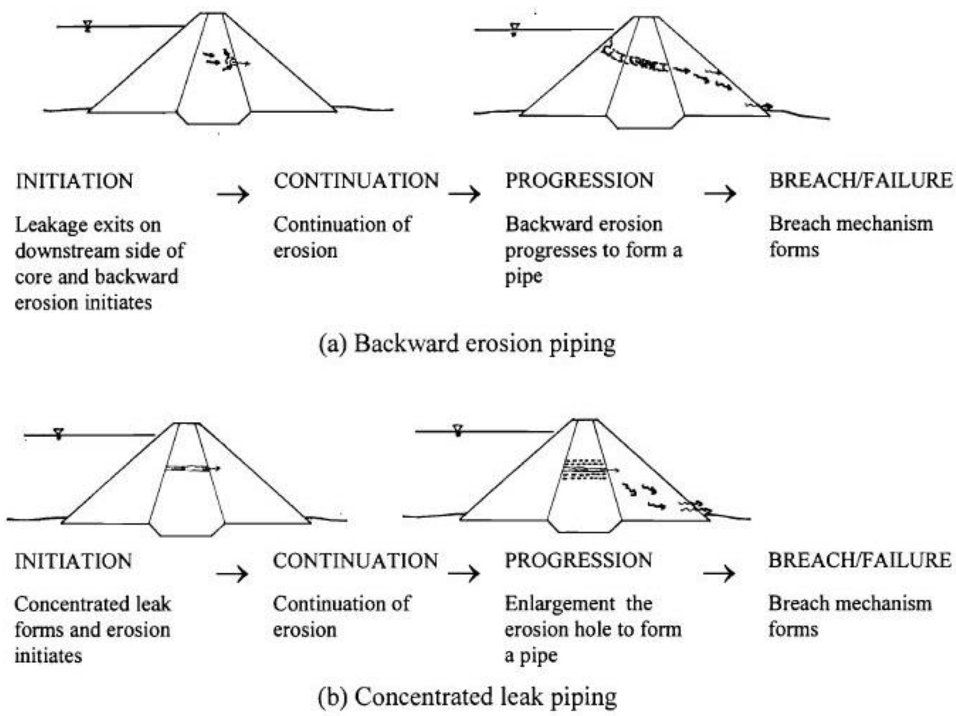


Figure 1.7 Model for development of failure by piping (a) backward erosion, and (b) concentrated leak[7)]

Kumamoto (1992) had presented the piping mechanism and it was expressed as the conception of event tree. The conception of the event tree is that it is a tool which can be used to estimate the possibility of failure by piping and the piping theory which was rearranged recently by Foster, Fell and Spannagle is widely recognized. Figure 1.6 illustrates the advanced failure path diagram[6)] for failure by piping through the dam body (Foster, Fell and Spannagle, 1998). This implies that the safety of the dam is closely related to the material characteristics of fill-type dam, since small grain size materials are moved as the internal erosion progressed.

In the connection with the internal erosion, Foster et al[6] presented a framework for estimating the possibility of failure of embankment dams by internal erosion and piping using event tree methods. The methods are explained that the erosion by infiltration can occur in the core zone including backward erosion and progresses back to the core placed in downstream side. Eventually, the erosion, it makes a breach failure[7] with water leakage. The breach failure is explained in the development of failure for backward erosion piping and concentrated leak piping as shown in Figure 1.7, the failure mechanisms involved in the initiation and progression stage has a different progress. The reason of the form of the different progress as mentioned the above can be explained through tension crack that occurred inside of the dam, crack by stress transfer effect between the filter and core zones that have different materials as a sand (filter) and core (clay), and the differences of the permeable layer in filter and clay zone.

As described above, the dam laboratory of the UNSW (Univ. of New South Wales) proposed the four steps caused by breaking down the piping incident into a sequence of events as follows (Foster and Fell 1999):

Concentrated leak or flow path → Continuation of erosion → Progression → Breach mechanism

In that context, Figure 1.8 shows the failure of the Teton Dam[7] (earthen dam for irrigation in Idaho, United States) which was a typical example of failure (June 6, 1976) by piping through dam body. The major causes are still being discussed, however, a study[8] of the dam failure of the Teton dam by Ian Smalley are presented as two mechanisms as follows;

a) First, the flow of water under highly erodible and unprotected fill, through joint in unsealed rock was started, and then it developed to form an erosion tunnel.

b) The second was cracking caused by differential strains or hydraulic fracturing of the core material.

In short, the permeable loess was found to be cracked. It is postulated that the combination of these faults allowed water to infiltrate through the dam body and led to internal erosion. These two mechanisms have the most persuasive in point of view based on the concept of event tree up to now.

Figure 1.8 Teton Dam collapsed in Idaho, United States on June 6, 1976
(Piping thorough dam body)[7)]

1.4 Possible Risks in the Core Heightened Dam

In connection to the heightening method for the existing dam, the piping problem which is based on the event tree, and since the given role of the core is to keep the safety of the dam, the seepage characteristics followed by the structure shape of the core is crucial. In regard to this, Figure 1.9 shows the actual heightening work for core heightening by inclined type in the site (site: Gyeryong reservoir, Gongju-si, Chungchungnamdo, South Korea, 2010). The Gyeryong reservoir, a 0.7 m thick upper layer of existing core was excavated from the core joint to connect the added new core and existing core in stable state, and the new core was heightened as an inclined-type along the downstream slope. Similary, the core heightened by vertical-type is also heightened to the construction procedure of the inclined core type. Here the note in the core heightening method, when investigating the piping phenomenon for the heightened dam, the core shape and state of the dam body that is under saturated and unsaturated condition should be considered. Based on the above information, the seepage problem such as concentrated leakage and backward piping caused by the core heightening method need to identify the detailed consideration for the safety of dam even the core shape and the narrow core width. As described above, the possible risks in the core heightened dam as an examples of the inclined-type core are as follows and Figure 1.10 shows the conceptual figure of the possible risks.

a) An existence of discontinuous core section between new and old core
b) A width of existing core has a still same width even after dam heightening work
c) Some old reservoirs dam are included for the heightening work.

Thus, it should be taken into consideration that the core shape must be adequate a core width when the piping passes the core zone. In regard to this, the large model test according to the core shape (inclined core and vertical core) is dealt with in section 1.4.

Figure 1.9 Heightening work for core heightening by inclined type
(Site: Gyeryong reservoir, Gongju-si, Chungchungnamdo, South Korea, 2010)

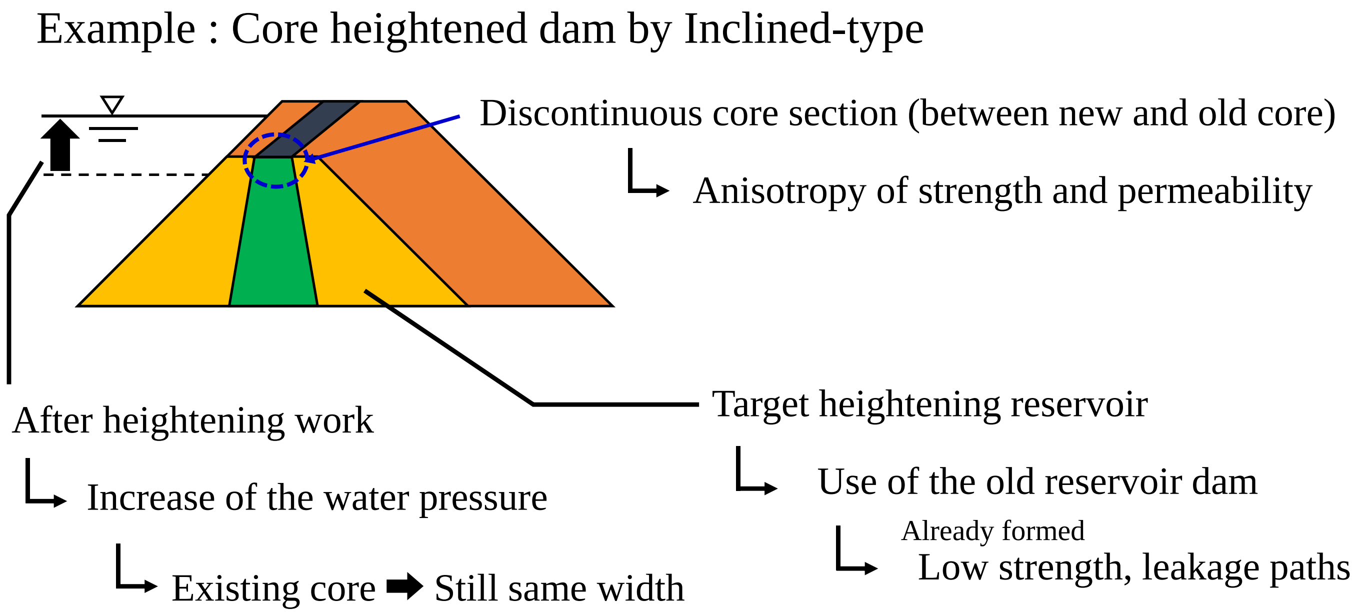


Figure 1.10 Conceptual figure of the possible risks in the core heightened dam (Ex: inclined-type core)

1.5 Experiment on Behavior of Inclined and Vertical Core Types of the Reservoir Dam

As described in section 1.3, in this section, the large model test was performed to consider the seepage characteristics on pore water pressure (PWP) and settlement caused by the core shapes (inclined and vertical core).

1.5.1 Materials used and large-model specifications

Samples used for the heightened model in this experiment were collected from a soil collection site in Gyeryong Reservoir located in Joongjang-ri, Gyeryong-myeon, Gongju-si, South Korea. The physical properties, which were performed for the soil characteristics used in the model test, and grain size curves of the collected samples are presented in Table 1.3 and Figure 1.10. The result of physical properties of the embankment zone (dam body zone) and core zone were classified into SC (embankment: clayey sand,) and CL (core: low plasticity clay,) by USCS (unified soil classification system), and it has a general grading soil characteristics of materials for construction. A soil tank for the experiment, 126 cm long, 270 cm wide, and 95 cm high, was manufactured using concrete, steel frames, and acryl.
Leakage of water from the soil tank was by coating the interior of the tank with silicone and waterproof paint. The preliminary experiment results revealed no significant water leakage that could have affected the results. The dam model used in the experiment was the heightened dam in Gyeryong Reservoir. The model scale was 1:20, and the slope angles upstream and downstream were both set as 1:2.0. Figure 1.12 shows a vertical core of the existing dam model. Here, inclined and vertical core zones were heightened to the upper part of the vertical core of the existing dam, as shown in Figures 1.13 (inclined-type) and 1.14 (vertical-type), and the heightened structural cores had the same scale. Samples used in the construction of the core heightened dam model were soils that had been passed through a 12-mm sieve to make them uniform; organic materials (weeds or grass) were removed to prevent any infiltration effect. Materials used for compaction were adjusted by setting optimum water content, and layer compaction was performed at intervals of 5 cm by using a specially manufactured wooden compaction rod; thus, 95% of the maximum dry density was achieved. The result of the density of each layer for dam model measured after layer compaction showed that dry density of soil was 1.61–1.89 g/cm^3 (1.76 g/cm^3 on average), and the dry density of the core was 1.57–1.70 g/cm^3 (1.64 g/cm^3 on average).

Table 1.3 Physical and mechanical properties used in the model test

Division	G_s	PI (%)	W_{opt} (%)	$\gamma_{d\,max}$ (gf/cm^3)	k_v (m/s)	C (kPa)	φ (Degree)	USCS
Embankment	2.65	9.2	14.0	1.76	5.75 E-07	16.7	24	SC
Core	2.69	15.5	23.0	1.61	3.11 E-08	34.3	9	CL

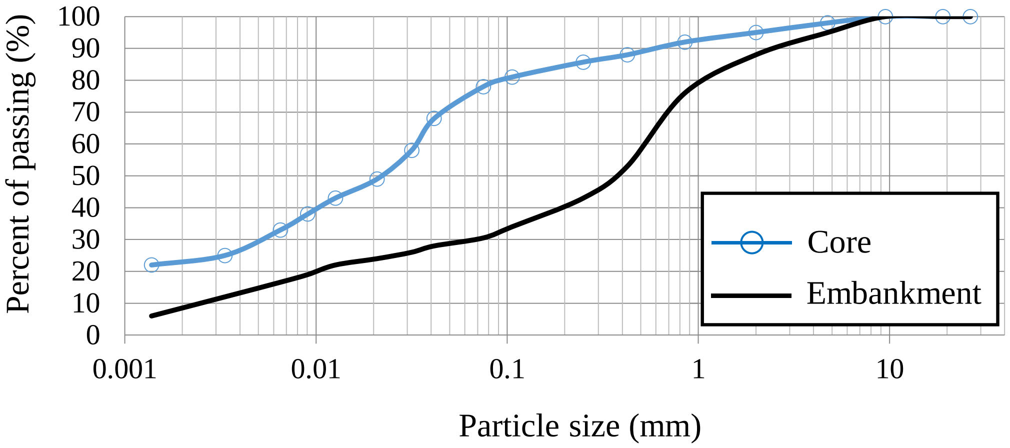


Figure 1.11 Grain size distributions of soil materials

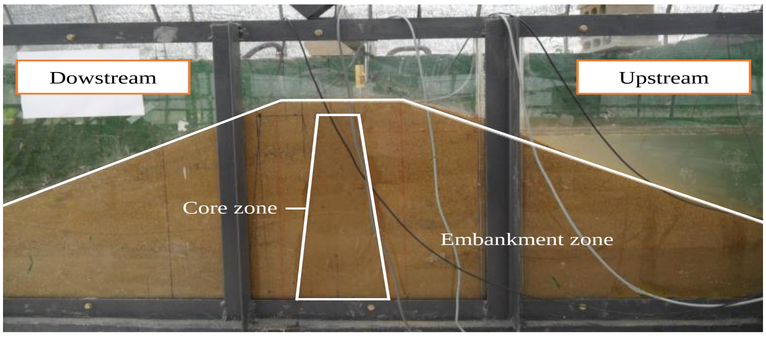


Figure 1.12 Dam model before heightening core

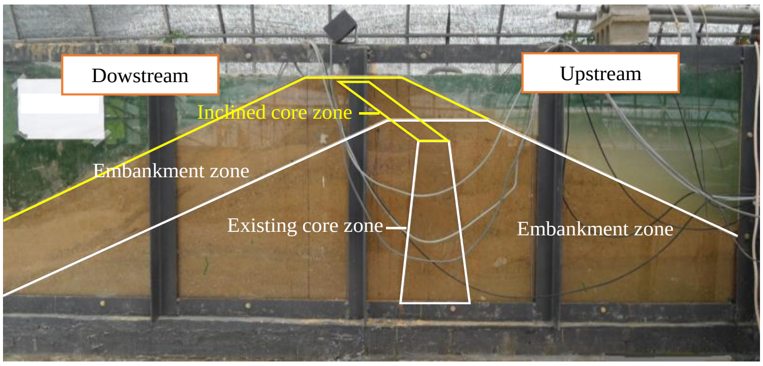


Figure 1.13 Dam model after heightened core by inclined-type

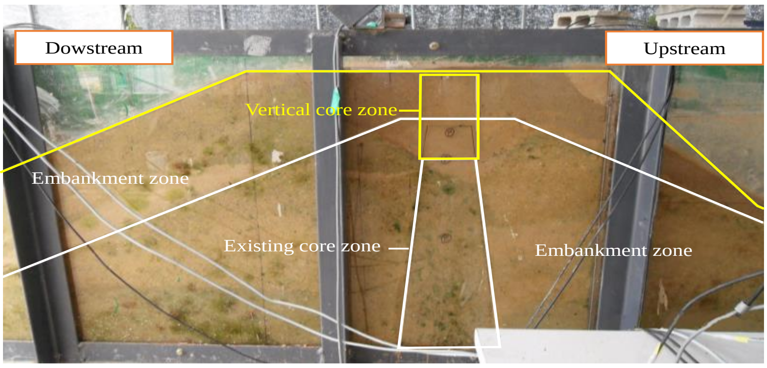


Figure 1.14 Dam model after heightened core by vertical-type

1.5.2 Measurement system

Figures 1.15–17 shows the installation locations of pore water pressure (PWP) meters and settlement meters. The laying interval between pore water pressure meters was set to cover a certain distance in the horizontal direction.

The laying depth for dam model was set, taking the slope height and inclination into consideration.

In addition, a linear variable displacement transformer (LVDT) extensometer was installed on the top of the model to observe the settlement trend corresponding to the type of the core, and the changes in settlement were recorded via a data logger.

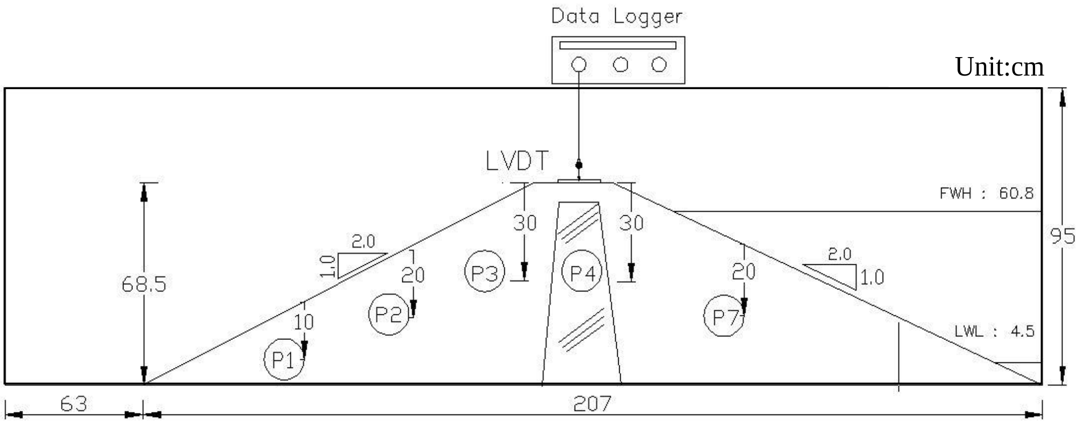


Figure 1.15 Installation locations of PWP and LVDT before the heightening core

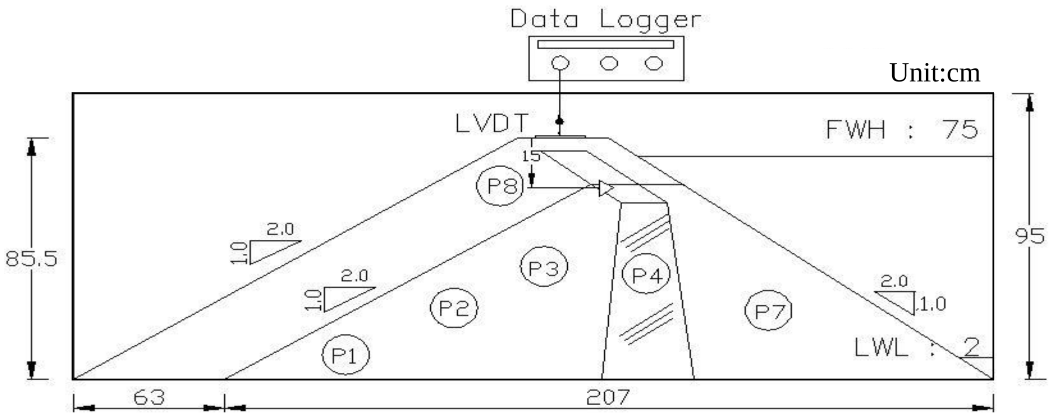


Figure 1.16 Installation locations of PWP and LVDT after heightened core by inclined-type

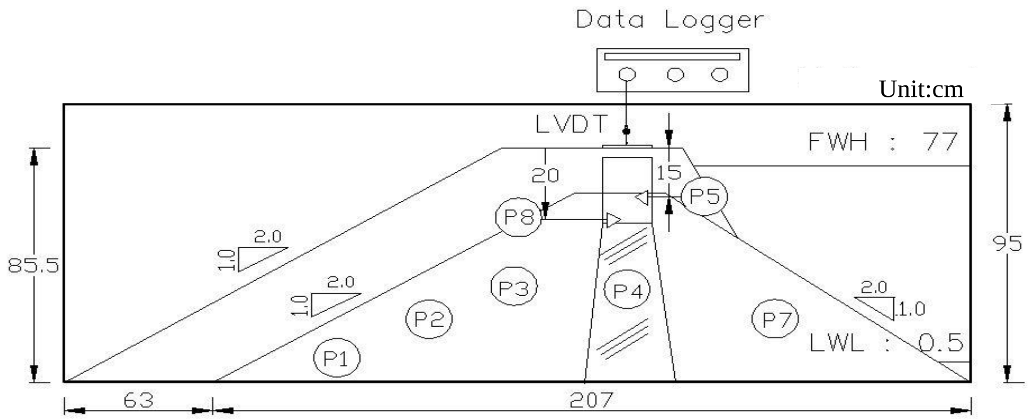


Figure 1.17 Installation locations of PWP and LVDT after heightened core by vertical-type

1.5.3 Experiment conditions

The existing reservoir dams were developed long ago—several years to decades ago—flow path inside the dams may have led to water leakage. Since the model constructed at first time (prior to core expansion) in this experiment has a high strength because of the early compaction, infiltration is less possible.

Accordingly, it was assumed that paths of water leakage had already formed in the model prior to core expansion, as in the actual existing dam, when changes in pore water pressure occurred in the installed core. Under this assumption, inclined and vertical cores were heightened on the top of the core.

Each model experiment was conducted thrice for 45 h each, and average PWP was considered in the analysis. Water was supplied up to the flood water level for about 30 min, and the time for sudden drawdown was set to about 15 min.

1.5.4 Similitude law applied to large model test

In order to understand the phenomena that can occur in a prototype heightened dam, a way to reproduce the phenomenon in a life-size model is the most accurate, but due to the lowering of the efficiency of cost or time for the modeling, the scale model reduction is generally used. However, when the scale of the model is reduced, because the model of the phenomenon is defined as non-linear or unsteady phenomenon, the flow state under the control of gravity in some cases governed by viscous forces can't be ignored (scale effect). Thus, the application of scaling ratio or similarities (i.e., geometric similarity, kinematic similarity, dynamic similarity) that satisfies the scale reduction model is desirable, but in reality, it is limited to reproduce with all the forces acting on the model at the same time except for a prototype testing. In this regard, the scale reduction model in this study is made of the soil material, and it deals with the infiltration tendency according to the shape of the heightened core (inclined and vertical types). This type of soil model, despite using same materials of the prototype dam, is may be difficult to apply the similarity of the model through theoretical calculations because they can't be reduced to the size of the pore and soil particles in the same proportion. In addition, since the planed width of the core may affect the test results, the similarity of the scale reduction model for satisfying the conditions can be quite complex.

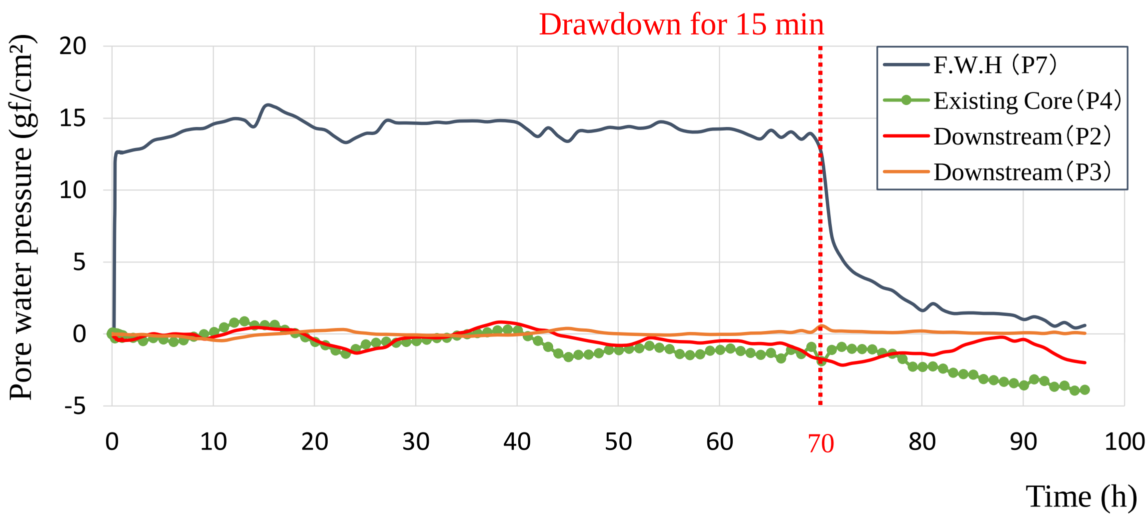
Therefore, in this experiment, the scale reduction model was determined by 1/20 of scale based on the core width that can measure or observe the infiltration phenomenon in a stable condition, considering the ease of production and the complex conditions for similarities.

This scale of the model in this experiment satisfies a scale range recommended through various model tests (Scale range:1/30-1/100 for spillway of dam, generally 1/100-1/1000 for horizontal scaling in river model test, 1/20-1/100 for vertical scaling of distorted model) and the general scale range applied for the embankment reduction model (Scale range 1/15-1/50), and thus it is expected that the model has enough scale to meet the purpose for basic infiltration experiment.

1.5.5 Result of change of PWP according to core shape

(a) ***Changes in PWP in the model before the heightening core***

Figure 1.18 shows the changes in PWP in the model before the heightening core.
With the increase in the water level, the PWP in the center core (P4) and downstream (P2, P3) were almost 0 gf/cm^2; the PWP became negative after water drawdown.
Overall, prior to core expansion, the model experienced minimum changes in PWP owing to the high strength of the core zone and embankment zone; this strength is a result of high compaction, as mentioned in chapter 1.4.3, and in this condition, water infiltration at the early stage is less possible.
Thus, prior to core expansion, the model is in a stage where infiltration is underway, and the model can be considered to be in a stable state with respect to changes in PWP.



. Figure 1.18 Changes in PWP in the model before the heightening core

(b) ***Changes in PWP in the heightened dam model by inclined core***

Figure 1.19 shows changes in PWP in the heightened dam model by inclined core.
The PWP in the existing core (P4) showed a trend of gradual increase, which indicated the beginning of infiltration in the existing model (see Figure 1.15). In this state, the inclined core was heightened, and the distribution of PWP was observed according to the water level variation.
The PWP of the inclined core (P8) increased rapidly initially (up to 3 h) as the water level was raised and then remained constant at about 3–4 gf/cm^2. Thereafter, once the water level was reduced, the PWP decreased gradually.

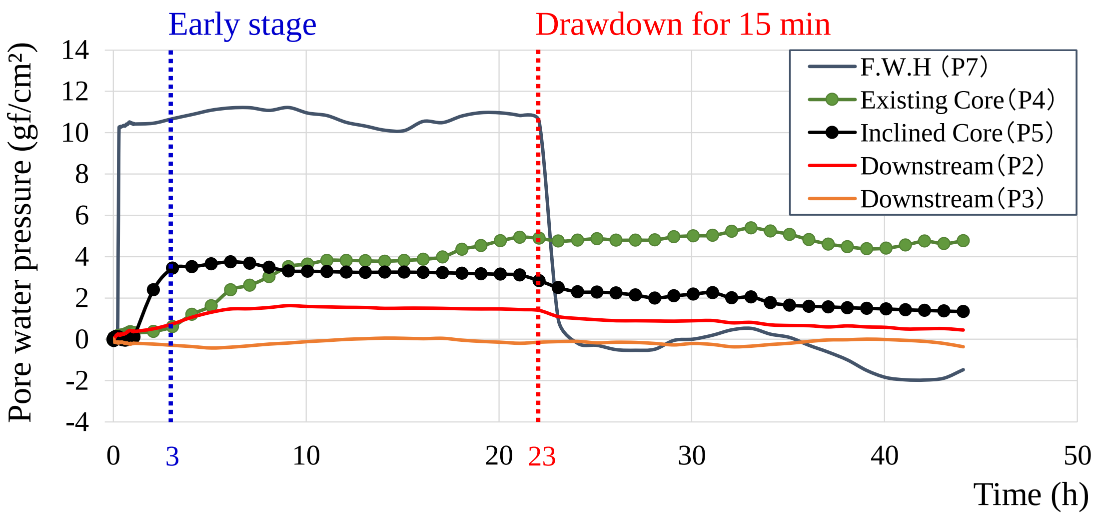


Figure 1.20 Changes in PWP in the heightened dam model by inclined core

A comparison of PWP in the existing core (P4) and in the inclined core (P8) showed that the former increased gradually, whereas the latter increased rapidly in the early stage (about 3 h). The reason for such increase in PWP in the inclined core (P8) was that either the core was narrow or the structure of the core made it vulnerable to infiltration.

In addition, the PWP (1.5-1.8 gf/cm^2) in the mid-point of the downstream-side (P2) increased gradually in the downstream direction, whereas the PWP (0 gf/cm^2) in the upstream direction (P3) did not change.

Overall, the water pressure was influential in the downstream direction because infiltration had started in the core. In addition, this implies that the core zone was formed by flow path due to time elapsed.

(c) *Changes in PWP in the heightened dam model by vertical core*

Figure 1.20 shows the changes in the PWP in the heightened dam model by vertical core.

As the water level increased upstream, PWP in the existing core (P4), a joint of the core (P8), and the vertical core (P5) showed an increasing trend in the early stage and then remained steady at 2-4 gf/cm^2. Here, the PWP in the joint of the core (P8) was higher than that in the vertical core (P5) and in the existing core (P4).

Here, the PWP in the core joint showed the most high value among the PWP measured in other position, and the core joint turned out to be vulnerable part by concentrated leak.

In the change of PWP observed in the downstream, the PWP at the mid-point of the downstream (P2) increased significantly in the downstream direction, thereby increasing the

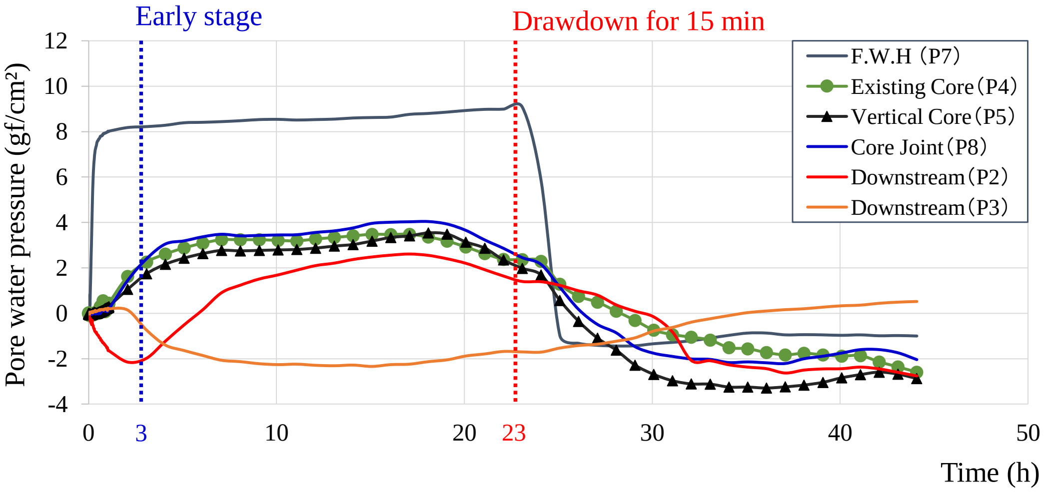


Figure 1.20 Changes in the PWP in the heightened dam model by vertical core

infiltration. Here, an increase in PWP along the downstream slope is related to an increase in PWP in the existing core (P4). This is because the strength of the existing core was reduced owing to its constant use from the previous model experiment (model prior to core expansion).

Meanwhile, the water level dropped, the decrease in the PWP in the cores (P4, P5, and P8) and along the downstream slope (P2) was large. This may be attributed to the formation of water leakage paths in the existing core (P4), which made infiltration easy.

1.5.6 Comparison of PWP according to the core shape

In general, immediately after completion of construction of the dam, the strength of the dam materials deteriorates because the increase in the water level is accompanied by the application of water pressure that acts as a load on the dam.

The degradation of strength could have caused internal erosion and sediment runoff due to infiltration, thereby increasing the possibility of dam collapse.

Therefore, it is important to identify changes in PWP in the early stage. In regard to this, the changes in PWP in the early stage corresponding to different types of core extensions were compared. The time for evaluation of PWP in the early stage was set to 3 h because the water level was stabilized within 3 h in the case of the inclined core (P8) where changes in PWP were rapid. Figure 1.21 shows the result of comparison of PWP in the inclined core (P8) and vertical core (P5) according to core shape in the early stage (time: 3 h). The figure shows that PWP (3.44 gf/cm^2) in the inclined core was twice that in the vertical core (1.74 gf/cm^2), indicating that the inclined core had a larger water pressure load in the early stage. This is because unlike the vertical core, the inclined core was not wide enough to resist the water pressure. As a result, this is likely to be a high possibility of formation of water leakage paths owing to the concentrated leakage when water pressure is acting on the heightened core for inclined-type.

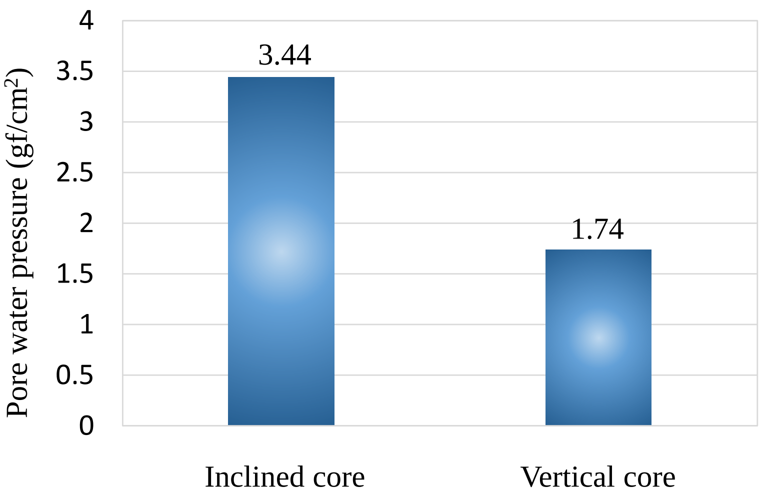


Figure 1.21 Comparison of PWP (P5) according to core shape in the early stage (time: 3 h)

1.5.7 Settlement distribution according to the core shape

Figure 1.22 shows a trend of settlement at the dam crest measured by LVDT according to core shape. As infiltration started in the inclined and vertical cores, settlement was underway slowly. After 13–15 h in the shape of the inclined core and about 35 h in the shape of the vertical core, the settlement showed a slightly increasing trend. This is because once the water was filled up to the soil zone in the upper stream, the core experienced water pressure load owing to the temporary blockage of water, resulting to temporary eccentricity.

Overall, the settlement in the vertical core showed a gradual trend over time, whereas that in the inclined core was underway.

As a result, the larger settlement in the heightened core for inclined-type may be expected that it extended up to the downstream-side and thus had wider settlement zone. This implies that the possibility of the core deformation and/or cracks is likely to be more venerable than that of the vertical-type.

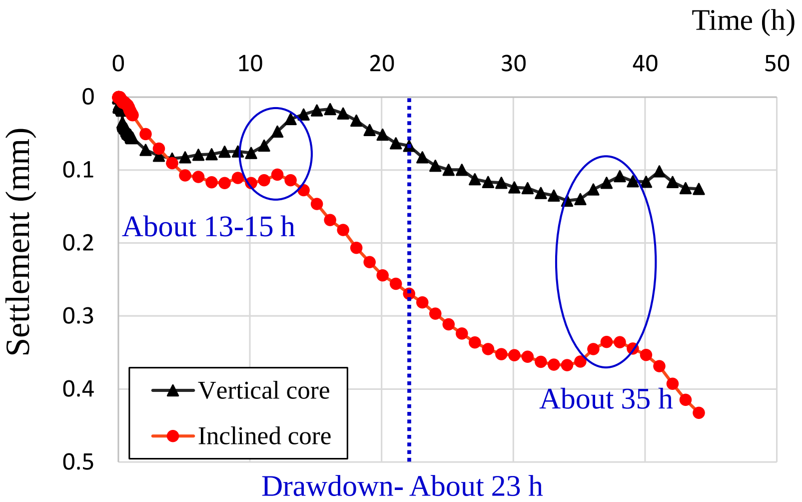


Figure 1.22 Trend of settlement according to the type of the core

1.5.8 Summary

In this section, large-scale model experiment was carried out to investigate the behavior of the heightened dam on both inclined core and vertical core.

(1) The PWP of the inclined core in the early stage was approximately twice that of the vertical core. This observation verifies that the inclined core experienced a larger water pressure load when the reservoir dam is heightened. In addition, the PWP in the joint of the core was higher than that in the exiting core or the expanded core. This was due to the vulnerability to infiltration at the joint; this is because the core joint was affected by concentrating infiltration from upstream water.

(2) Settlement in the inclined core was larger than that in the vertical core. This was because the inclined core was heightened in the horizontal direction so that its settlement area was wider.

From the experiment result, the core heightened dam by inclined-type was considered to be vulnerable on infiltration and settlement. This results imply that the repair and/or reinforcement costs regarding the treatment of a crack and water leakage in the heightened core for inclined type may increase more than that of vertical-type. In addition, the life time the core heightened dam can be reduced since the infiltration is constantly progressive due to its material characteristics (clay, silt and sand) of the dam. Therefore, the plan of a core heightening work by inclined-type shall be established for a rational maintenance and stabilization that can guarantee the life time of the heightened dam safety in the long run.

1.6 Seismic Performance of the Core Heightened Dam by Inclined-Type Related to an Earthquake

1.6.1 Tendency of earthquake and older dam in Korea

The frequency of earthquakes[11)] in Korea has increased in recent years as shown in Figure 1.23 (KMA, 2012). Moreover, owing to large earthquakes that have occurred in nearby countries such as China (e.g., the great earthquake in Sichuan in 2008) and Japan (e.g., the great earthquake in eastern Japan in 2011), the seismic performance of soil structure is becoming increasingly more important in preparation for future earthquakes.

In that context, seismic design is applied to large dam constructions but a considerable proportion[2)] of small and medium-scale dams such as reservoirs were built a long time ago. Here, the older dam was expected to have a lower seismic performance level compared to that of the dam that is constructed in modern times. In regard to this, seismic coefficient method in Korea was generally used for stability evaluations of the heightened reservoir dam but older dams are likely to show different patterns from those obtained through analytic results because of the erosion by elapsed time.

Thus, the reflection of the analysis results obtained from seismic coefficient method has a limited application to the older dam as the accident patterns that occurred in older dam are varied.

Therefore, it is crucial to understand a more detailed behavior on permeable and dynamic performance for the heightened dam.

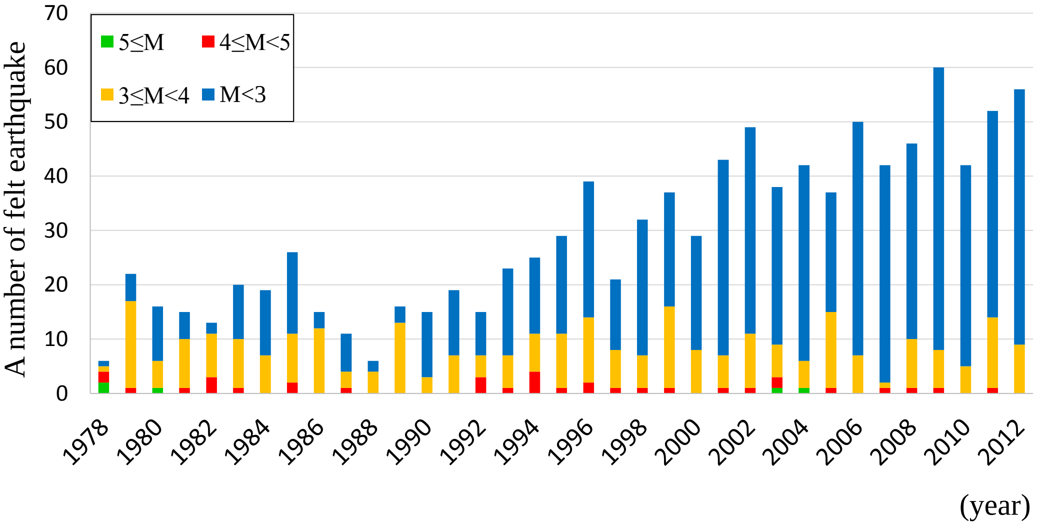


Figure 1.23 Number of frequency of earthquakes in Korea

1.6.2 Relation between dynamic performance influence and heightened core by inclined-type

The interior shape of the core in the core heightened dam by inclined-type becomes a tilted structure owing to the changes from the upper part of an existing vertical core to inclined core. As a result, the seepage line in the downstream body can be changed to an overhanging like shape. In this tilted structural core, the possibility of damage during earthquake is expected to be high at the core joint due to the core deformation caused by the stress concentration in the position (core joint) where the shape of the core is changed, and this process can also be connected to the piping phenomenon at the core joint by concentrated water leak as described in section 1.4.3.

Since the existing and heightened cores have different ranges of strength and permeability despite having the same material, the zone of the core joint would be vulnerable to the infiltration by deformation and/or cracks.

As a result, the core joint zone of the downstream as shown in Figure 1.24 is likely to be appeared as patterns like the backward erosion piping as mentioned in section 1.4.3.

In addition, the core under dry season is likely to be brittle (deformation and/or crack) owing to material characteristics of clay. For instance, clay becomes brittle since it reaches its plastic zone as time elapsed. In this state, if rainfall raised the water level of the upstream and is acting on the dry core, the safety of the core joint and inclined core zones is expected to be low due to the infiltration acting on the part of cracking. As a result, the piping that passes through the dam body from inclined core may be more developed as the change of the pore water pressure in the heightened core (inclined-type) becomes larger based on the result obtained from section 1.4.

Therefore, the core heightened dam by inclined-type is expected to have complicated influence on seepage and dynamic behavior. Thus, it is crucial to perform dynamic analysis for the determination of a more detailed behavior for heightened structural core, and a more stable core-structure design-method should be established to enhance the stability of the core heightened dam by inclined-type.

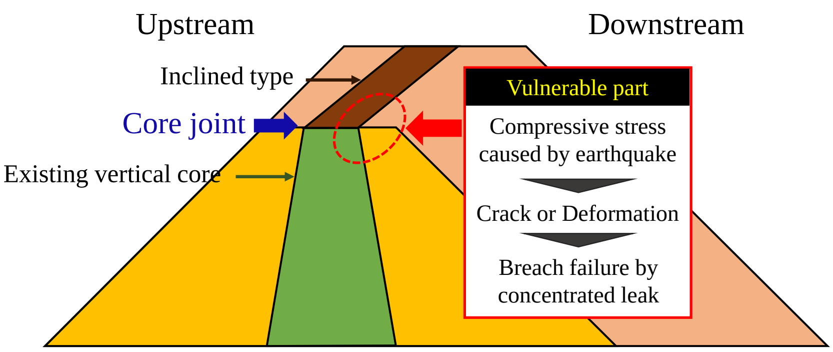


Figure 1.24 Conceptual figure of the vulnerable part (core joint of the downstream) for concentrated leak and backward erosion during an earthquake

1.7 Research Subjects and Composition

1.7.1 Location and field scale of target reservoir

Figure 1.25 shows the location of the target reservoir (Gyeryong dam) to which this study gives attention to. The dam was constructed in 1964, and the heightening construction for inclined core-type started in 2009 and completed in 2011[9].

Table 1.4 shows the field scale[9] of the Gyeryong reservoir. It also shows that there is a 40% increase in the water after the height of the reservoir was heightened by 2.8 m.

Figure 1.25 shows a sectional plan for heightening the Gyeryong reservoir. For the heightening the Gyeryong reservoir, a 0.7 m thick upper layer of existing vertical core was removed from the core zone, and the core was heightened as an inclined-type along the downstream slope. The heightened core width from the upper part of the existing vertical core was determined at 2.0 m (See Figure 1.26) based on the design standard[10]; determination of the thick ranging from 1.5 to 3.5 m under the dam height less than a 30 m.

The reason that Gyeryong reservoir is chosen as the target reservoir of this study is that the dam has existed for 50 years already, accordingly its existing body and spillway are old. Moreover, getting basic information is easy since there are many core heightened dams around the Gyeryong reservoir. Further, the heightening height of the dam measures 2.8m, which is higher than the average height (2.5m) of a core heightened dams by vertical or inclined-types.

Table 1.4 Field scale of the Gyeryong reservoir[9]

Dimension	Before extension	After extension
Dam type	Zoned earth fill dam	
Height	14.30 m	17.10 m
Length	288 m	300 m
Width of dam crest	6.00 m	6.00 m
Flood water level	60.95 m	62.00 m
Full water level	59.43 m	61.00 m
Effective storage capacity	3,412,410 m^3	4,717,730 m^3

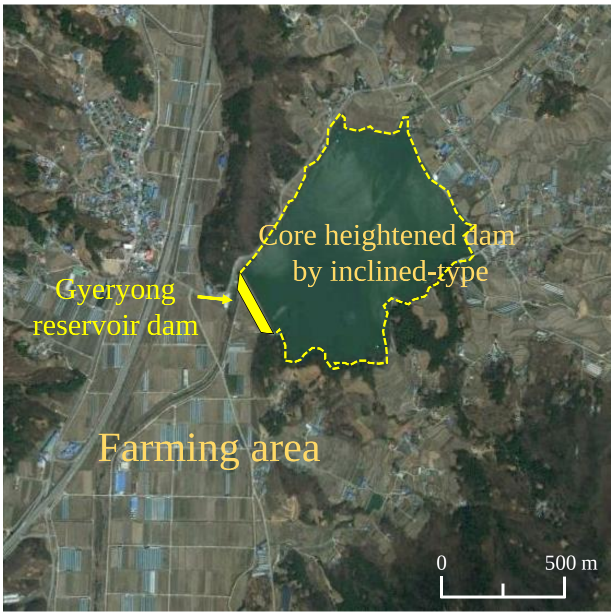


Figure 1.25 Location of the target reservoir; Gyeryong reservoir (Source: Goggle earth, 2015.5)

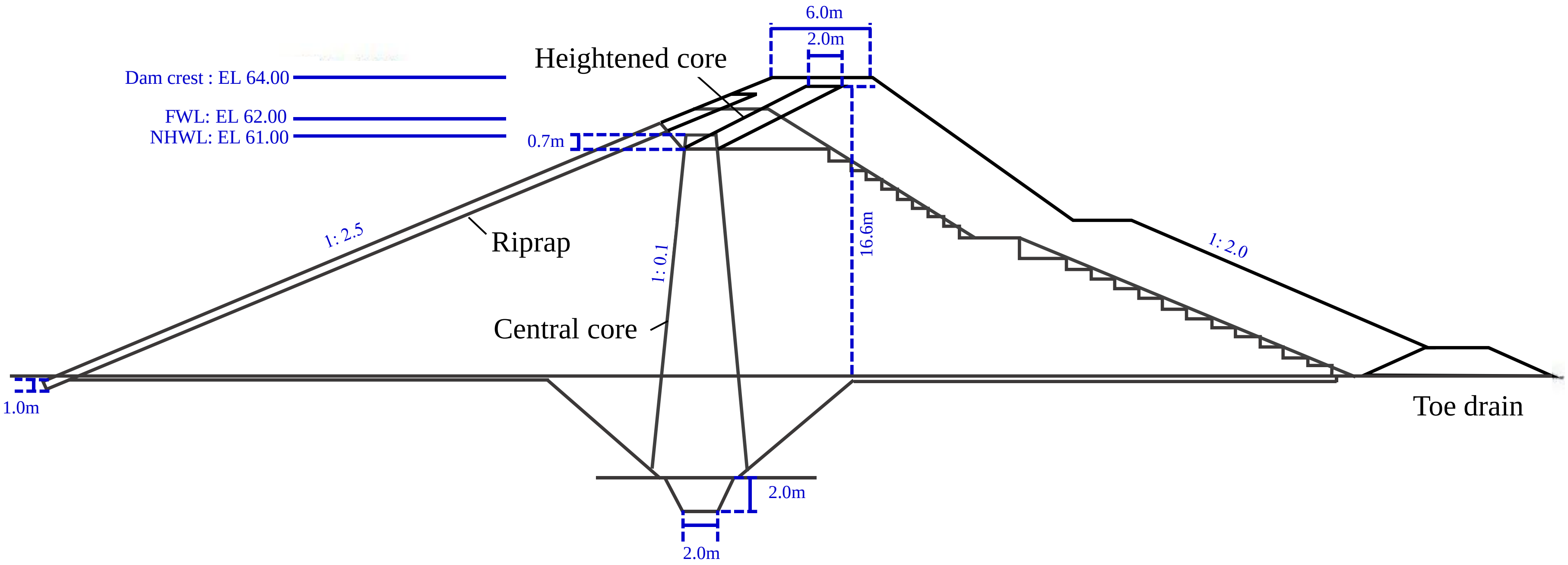


Figure 1.26 Sectional plan for heightening the Gyeryong reservoir

1.7.2 Proposal of expanded structural core construction method

As described in section 1.1-5, the main causes that may be occurred in the heightened dam by inclined core-type on permeable and dynamic problems are summarized as follows.

(a) Most of the reservoir dams being heightened are old, leakage paths inside the dam body may exist. If there are structural failure and accidents in the dam body, the structure is likely to be failed since soil materials can be taken out through the leakage paths during the piping phenomenon.

(b) The existing and heightened cores have different ranges of strength and permeability despite having the same material, the zone of the core joint may be vulnerable to the infiltration by concentrated leak.
Thus, the core heightened dams by inclined-type shows a shape of the entire structural core becoming asymmetric, it may be vulnerable to the seismic effect (deformation or crack) in the position (core joint) where the shape of core are changed regarding the recent increasing trend of earthquakes.

(c) The interior shape of the core in core heightened dam by inclined-type becomes a tilted structure owing to the changes from the upper part of the existing vertical core to the inclined core. As a result, the seepage line in the downstream body can be changed to an overhanging shape. In regard to this, the possibility of damage during earthquake is expected to be high at the core joint due to the core deformation caused by the stress concentration in the position (core joint) where the shape of core are changed, and this process can also be connected to the piping phenomenon at the core joint.

Once the permeable problem occurs in the downstream slope, a seepage line may raise toward the upper side by elapsed time; as a result, the cost of controlling the seepage line will increase. In connection with the cost of controlling the seepage line, sheet pile and grouting methods are generally used as fundamental alternatives to the core repair and/or reinforcement but the material cost is expensive. Thus, the most economical alternative is the method of expanding the core in the position in which a vulnerable part on permeable and dynamic behaviors is larger. This method is expected that economic perspectives and constructability contribute to keeping the dam safe for a long-period because the cost of the core materials is cheaper than that of sheet-pile and grouting materials, as means of enhancing the structural reinforcement.

To present the expanded structural core construction method, a cross-section of the dam model (Gyeryong reservoir dam) was justified as the FEM analysis model as shown in Figure 1.27.

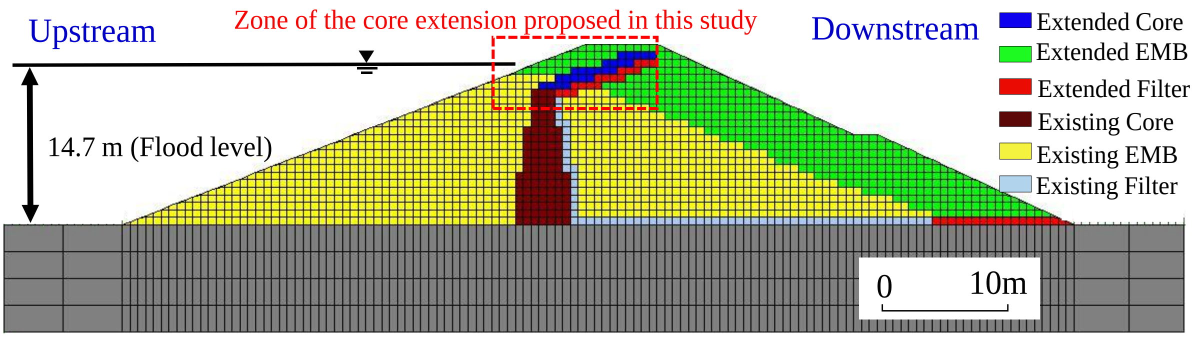


Figure 1.27 cross-section of the dam model (Gyeryong reservoir dam)

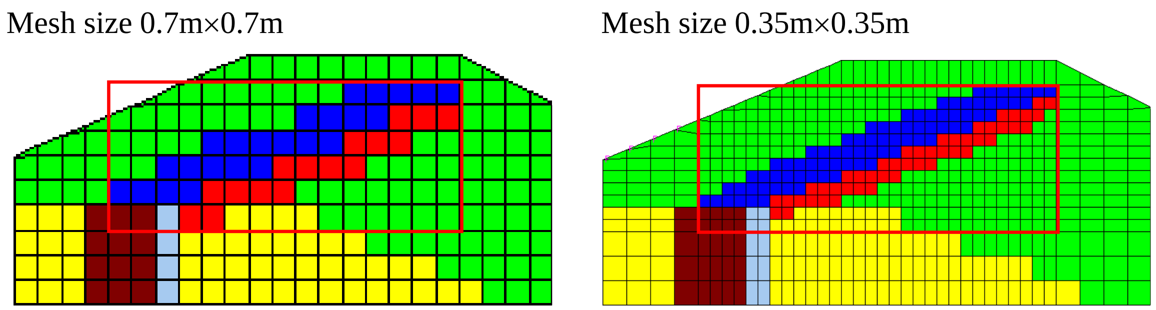


Figure 1.28 Comparison of the mesh model according to the mesh size and shape

The mesh shape of the core joint zone applied to the analysis model was determined to be a square (size 0.7 m×0.7 m) shown in Figure 1.28. Here, the reason to set the square mesh shape is that the mesh shape of the core joint zone can be complex because the core shape is changed to inclined core-type. This would result in analytical error such as converges or diverges due to the larger differences of the permeability between the narrow widths of the core (very low permeability) and filter (very high permeability). Thus, the uniform mesh shape was selected, and it is expected to be in ease of the mesh formation and the shortened hours of the calculation. In that context, the impact on the analysis result according to the size and shape of a square mesh model should be verified. In this regard, the mesh size divided into a size 0.35 m×0.35 m and size 0.7 m×0.7 m as shown in Figure 1.28, and it was compared by seepage flow analysis. As a result, the seepage quantity of the mesh size 0.35 m×0.35 m is shown to be about 1.03 times larger than that of the mesh size 0.7 m×0.7 m, thus the impacts on the mesh size 0.35 m×0.35 m are expected to be very low. Then the mesh size 0.7 m × 0.7 m is applied in the following research.

To reinforce the structure of the core joint, which is considered susceptible to seepage or deformation, author proposed the expanded structural core construction method which is the expanded scale of the core from the downstream-side core joint as shown in Figure 1.29. In regard to this, author proposed three kinds of the expanded scale of the core joint. Case 1 represents the basic model of the actual core heightened dam (Gyeryong reservoir dam) without any change in the height or width of the core joint. The other three models simulate three different core structures, in which the core volumes expanded from three different depths (Case 2: 0.7 m; Case 3: 1.4 m; Case 4: 2.1 m) below the core joint to the downstream side. Figure 1.30 represents the definition of the scale of expanded cores, and Table 1.5 presents detailed dimensions of each model proposed in this study.

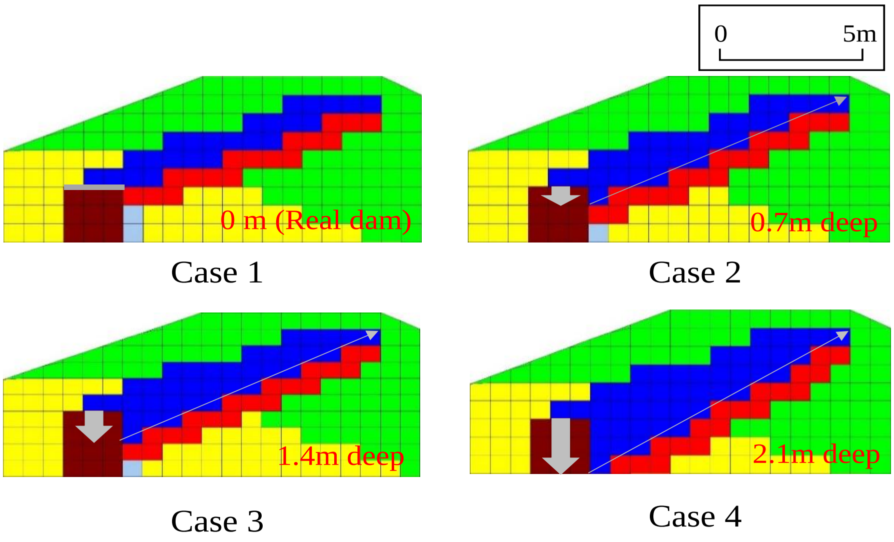


Figure 1.29 Expanded structural core construction method proposed in this study

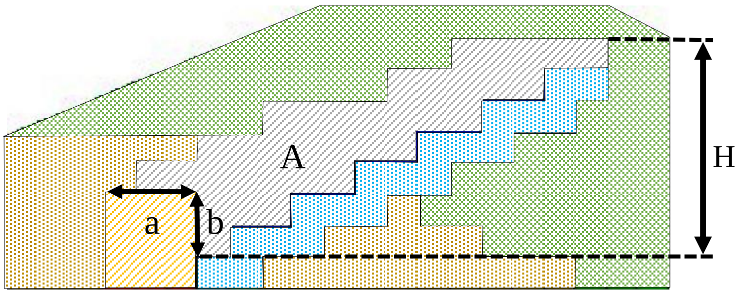


Figure 1.30 Definition of the scale of expanded cores

Table 1.5 Detailed dimensions of each model for the expanded structural core

Case No.	Scale of the expanded core		
	Zone	Height	Connected length with existing core a+b
Case 1	11.76 m^2	3.50 m	0.70 m
Case 2	13.72 m^2	4.20 m	1.40 m
Case 3	17.15 m^2	4.90 m	2.10 m
Case 4	21.07 m^2	5.60 m	2.80 m

1.7.3 Research subjects

Figure 1.31 illustrates the outline of the objectives covered. The core heightened dam by inclined-type, as mentioned in section 1.2, results in the shape of the entire structural core becoming asymmetric because the inclined core zone is newly heightened on the top part of the existing vertical core to the downstream direction. Given the role of the core in resisting the upstream water pressure, the asymmetric structural core in the position (core joint) where the shape of core are changed is expected to be vulnerable to permeable and seismic effects.

In that context, safety evaluation of the core heightened dam was performed by the seepage flow and slope safety analysis but these were not considered up to the scope of core heightened zone. Meanwhile, for the safety analysis of an earthquake, seismic coefficient method was generally used for stability evaluations of the core heightened dam but most of reservoir dam are old, and old dams are likely to show different patterns from those obtained through analytic results. Thus, it has an importance to perform dynamic response analysis for the determination of a more detailed analysis for the heightened dam and a more stable core-structure are needed to enhance the stability of the core heightened dam by inclined-type.

In this study, therefore, authors propose the expanded structural core construction method, which is a construction method for the core heightened dam to expand the core joint between an old core and a new core, as three kind of the expanded scale at the core joint.

In addition, the three kind of the expanded scale at the core joint was analyzed for the identification of the core heightened dam on permeable and seismic effects by using the seepage flow and dynamic response analysis. Meanwhile, there is an afraid that the construction cost will increase as the scale of the core was expanded. Thus, an economic analysis to decide the optimal scale of the structural core considering the life cycle of the core heightened dam was assessed as means of enhancing the economically efficient but also structurally feasible for future heightening plan.

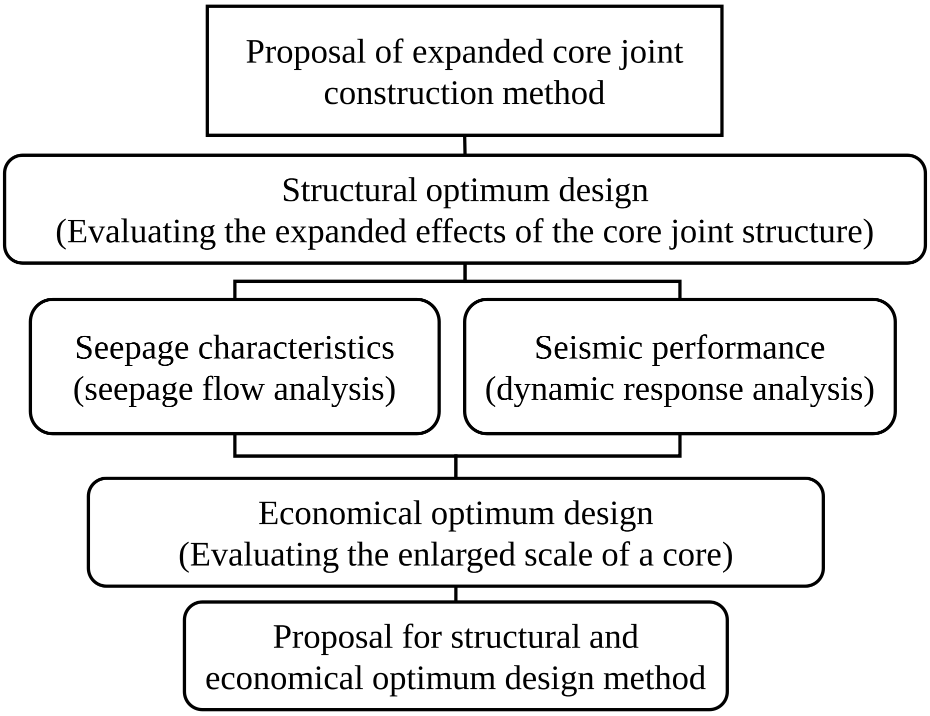


Figure 1.31 Outline flow chart of the subjects

1.7.4 Composition of the thesis

Korea is considered to have a relatively lesser earthquakes hit in comparison with East Asia countries. However, owing to large earthquakes that have occurred in nearby countries such as China (e.g., the great earthquake in Sichuan in 2008) and Japan (e.g., the great earthquake in eastern Japan in 2011), the seismic performance of soil structure is increasingly becoming more important in preparation for future earthquakes regarding the recent increasing trend of earthquakes in Korea. In connection to this, because the demands for a heightening work securing water resource in relation to future climate warming is increasing in recent years. Thus, it is crucial to understand a more detailed behaviors on permeable and seismic subjects for core heightened dam. In that context, Korea has been using a static analysis method in general to evaluate the safety of the heightened dam and it mainly focused on the slope sliding or settlement problems in the present time. However, a subject for the core problem such as the piping through the dam body besides the sliding or settlement problems for the safety factor evaluation was not considered up to now. In regard to this, the core joint for the heightened dam by inclined core is expected to have a complex influence on the seepage and dynamic behavior because the core shape was changed to inclined-type from the upper part of existing core.

In general, the piping through the dam body is not identified clearly because the core was installed inside of the dam. This is related in persisting period of time for a reservoir dam, and thus a consideration of the reducing the damage and/or loss of the life cycle in the core heightened dam by inclined core has the importance with respect to increasing trend of the heightening work of the reservoir dam. Therefore, the expanded structural core construction method proposed in this study was applied to the position where a vulnerable part on permeable and dynamic behaviors are larger, moreover, it identified the core expanding effect to enhance the heightened dam performances in the long run. Figure 1.32 illustrates the composition of this dissertation, and the following is a brief outline of the topics covered.

Chapter 1 contains a general background and objectives including the results of the previous study for large model test and the background knowledge of the failure mode and the like. In addition, the necessity for the reinforcement of the vulnerable part (core joint) in the heightened dam by inclined core-type was claimed, and the expanded structural core construction method is being proposed.

In chapter 2, the effects of the expanded core scale on seepage characteristics of the heightened reservoir dam were summarized. Concretely, the possible factors that cause a dam accident during piping through the dam body were considered in FEM seepage flow analysis method. The checking point of the seepage flow analysis give an attention to the piping phenomenon caused by core cracks at the core joint regarding the flow velocity, seepage quantity, hydraulic and saturation degree and like.

In chapter 3, the effects of the expanded core scale on dynamic performance of the heightened reservoir dam were summarized. Concretely, the possible factors that cause a core cracks or deformation during an earthquake were considered in FEM dynamic analysis method.
In addition, in order to identify the effects of the dynamic performance of the heightened dam according to the expanded core scale, a sinusoidal waveform and seismic motions were used, and the natural period and the shear stress distribution that occurred in the core joint were considered.
In chapter 4, expanding effects and economical optimum design of the inclined-type structural core for heightening reservoir dam were discussed. On the basis of the results obtained in chapters 3-4, accordingly, to expand the core scale, there is an increase in the construction cost; the optimum structural core scale must be determined to assess whether expanding the core is an economical effect as a means of securing water resources. Therefore, leakage water price was assessed with respect to the construction cost incurred during the expanded scale of the core, and an optimal core scale was proposed with respect to the design water value.
In chapter 5, the conclusions and remarks based on the results obtained from Chapter 1-4 were outlined.

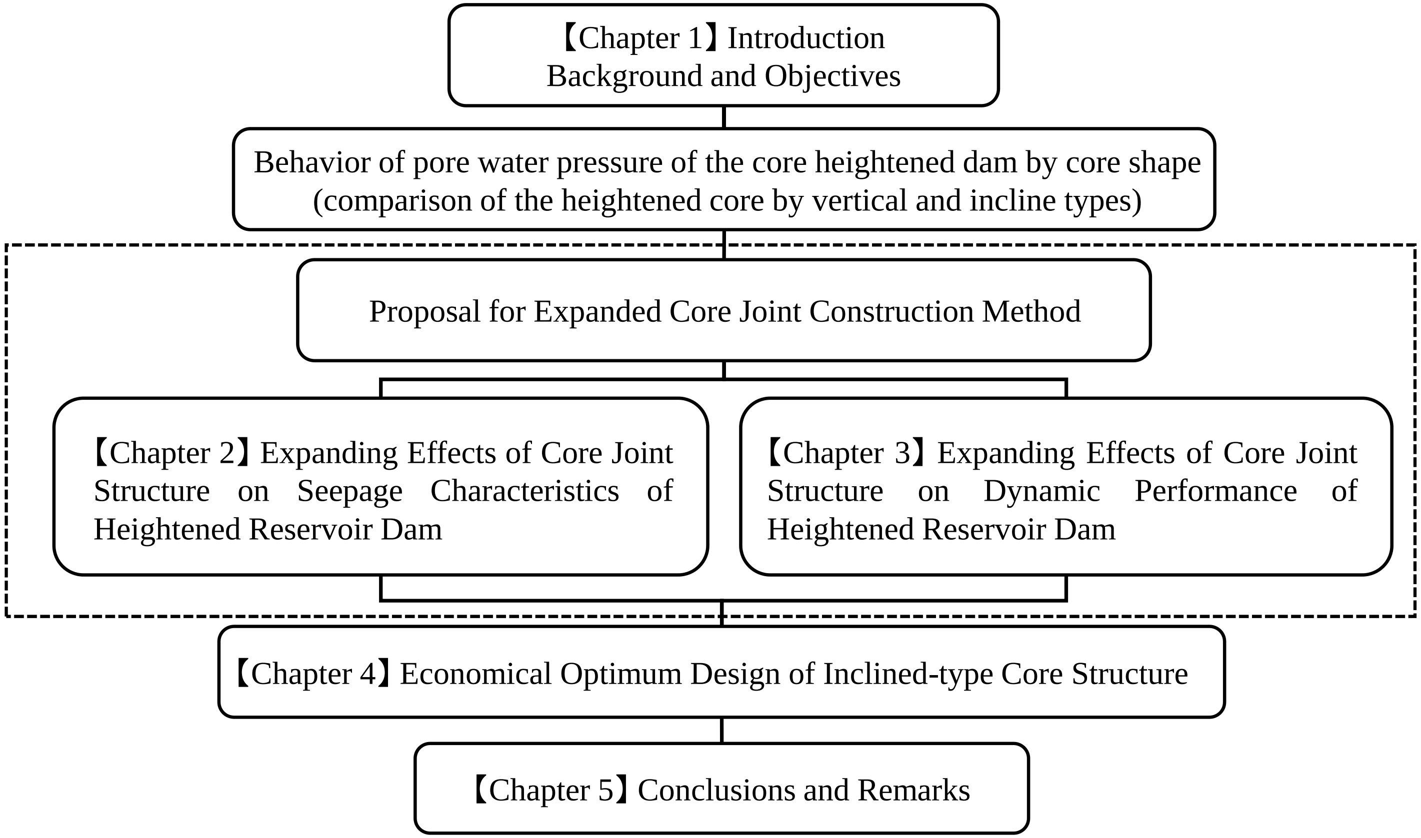


Figure 1.32 Composition of the thesis

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Chapter 2

2. Expanding Effects of Structural Core on Seepage Characteristics of the Heightened Reservoir Dam

In this chapter, the expanding effects of structural core on seepage characteristics of the heightened reservoir dam are discussed by using FEM seepage flow analysis method.
To identify the seepage characteristics for designing an inclined-type heightened reservoir dam, it was evaluated by using four kinds of model as described in section 1.6.2 (expanded structural core). The followings are the considered part in the seepage flow analysis.
Firstly, the possibility of piping of the core heightened dam by inclined-type was evaluated on seepage quantity and hydraulic gradient. Secondly, flow velocity at the core joints and the seepage quantity through the newly heightened core (inclined-type) was considered. Last, the effect of saturation of the core under the conditions of water-level drawdown was evaluated.
On top of that, this study considered the coefficient of permeability of the core heightened dam that can be applicable to the heightening work as means of enhancing the efficiency of the cost and the construct abilities.

2.1 Modeling Approach

An unsteady-state seepage analysis was performed using the FEM program VGFlow2D[1)] to investigate the seepage characteristics in the heightened core. VGFlow2D represents a saturated-unsaturated seepage analysis whose governing equation is the Richards equation[2)].
The seepage characteristics of unsaturated soils were represented by a soil-water characteristic curve as the van Genuchten model, whereby vertical two-dimensional modeling was applied for analysis.
For the input soil-water characteristic of saturated-unsaturated condition, representative water characteristic curves[3)] built in program were applied to each material (core-clay, embankment-sandy soil, filter-sand, ground foundation- clay).

2.2 Conditions of Application for Seepage Flow Analysis

2.2.1 Boundary condition

In seepage flow analysis, a change of water level is important variable to influence the seepage characteristics and safety of the reservoir dam in relation to the piping caused by infiltration in the downstream-side. In regard to this, this study considered a change of water level during life cycle to estimate the leakage quantity based on records of the Gyeryong reservoir.

Figure 2.1 shows the rainfall record in the Gyeryong-myeon (rainfall meter: about 500m far from the Gyeryong reservoir) and the change of water level in an upstream-side of the reservoir in 2012-2013 years (Records of water level were measured from 2012; heightening work of the Gyeryong reservoir was completed in 2011). Table 2.1 represents the results obtained from the seepage flow analysis on the leakage quantity and the rate of Q_{ave}/Q_{max} according the change of water level. Here, the Q_{max} illustrates a constant leakage quantity (57.70 m^3/d) under the maximum flood water level constantly in the upstream-side. On the other hand, an average leakage quantity (Q_{ave}) calculated from each leakage quantity considering the real change of the water level in 2012-2013 years shown in Figure 2.1 was appeared to be 32.36 m^3/d, and it is occupied as 56.1% of leakage quantity in comparison of the maximum constant leakage quantity (Q_{max} : 57.70 m^3/d).

Based on the above, the rate of Q_{ave}/Q_{max} is a different, but in this paper, the water level is considered to be maximum flood water level (F.W.L) constantly all year around, because the purpose of this paper is to do the relative comparison between Case 1 to Case 4.

Figure 2.2 shows the condition of application for the water level in seepage flow analysis, the upstream water level was raised from the foundation (0m) to the flood level (14.7 m) over thirtieth days, and the flood water level was maintained until the seepage line of the core that was newly heightened stabilized.

For water drawdown condition, water level (14.7m) are declined over ninety days, which is based on the irrigation date having the high water consumption from May to July for farming work and then maintained for thirtieth days.

For condition of seepage surface for the heightened dam model, the seepage surface set to the ranging from the front end of downstream slope (0m) to the berm height (8.4m) considering the increased water storage due to the heightened work.

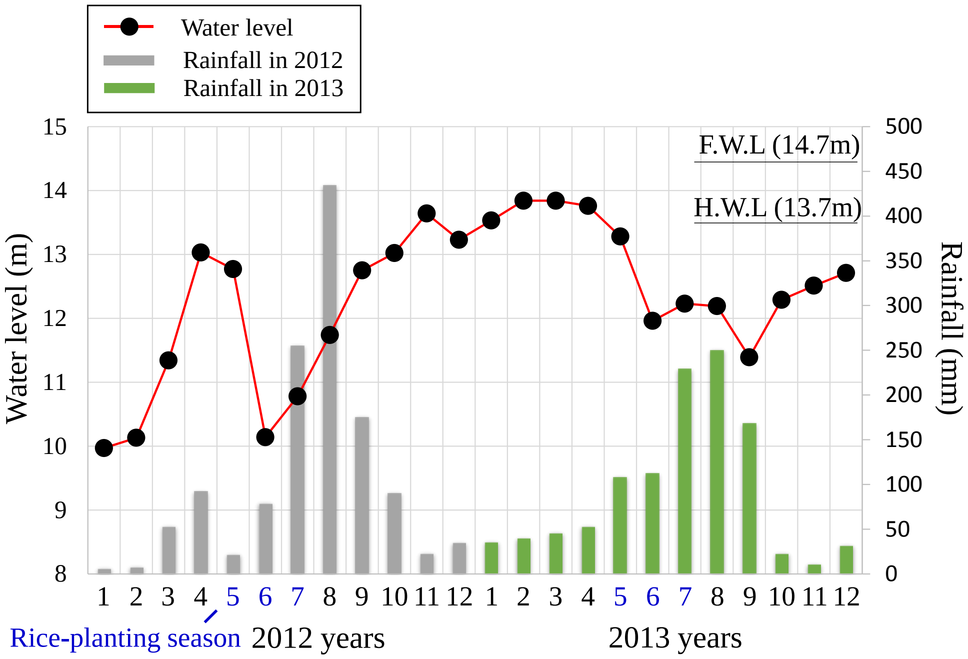


Figure 2.1 Rainfall trend and the change of water level in upstream-side in 2012-2013 years

Table 2.1 Results obtained from the seepage flow analysis on the leakage quantity and the rate of Q_{ave}/Q_{max} according the change of water level

Year	Month	Water level (m)	Rainfall (mm)	Leakage quantity (m^3/d), Q_{ave}	Q_{ave}/Q_{max}	Percent (%)
2012	1	10.0	6	20.45	0.35	35.4
	2	10.1	8	20.64	0.36	35.8
	3	11.3	53	21.24	0.37	36.8
	4	13.0	92	22.12	0.38	38.3
	5	12.8	22	23.68	0.41	41.0
	6	10.1	79	25.33	0.44	43.9
	7	10.8	255	26.02	0.45	45.1
	8	11.7	434	26.33	0.46	45.6
	9	12.8	175	27.11	0.47	47.0
	10	13.0	90	28.59	0.50	49.5
	11	13.6	23	30.35	0.53	52.6
	12	13.2	35	32.19	0.56	55.8
2013	1	13.5	36	33.85	0.59	58.7
	2	13.8	40	35.67	0.62	61.8
	3	13.8	46	37.64	0.65	65.2
	4	13.8	53	39.50	0.68	68.5
	5	13.3	108	40.95	0.71	71.0
	6	12.0	112	41.91	0.73	72.6
	7	12.2	229	41.78	0.72	72.4
	8	12.2	250.0	41.47	0.72	71.9
	9	11.4	168.0	40.88	0.71	70.8
	10	12.3	23.0	40.10	0.69	69.5
	11	12.5	11.0	39.55	0.69	68.6
	12	12.7	32.0	39.19	0.68	67.9

*Q_{max} (Leakage quantity in maximum flood water level)

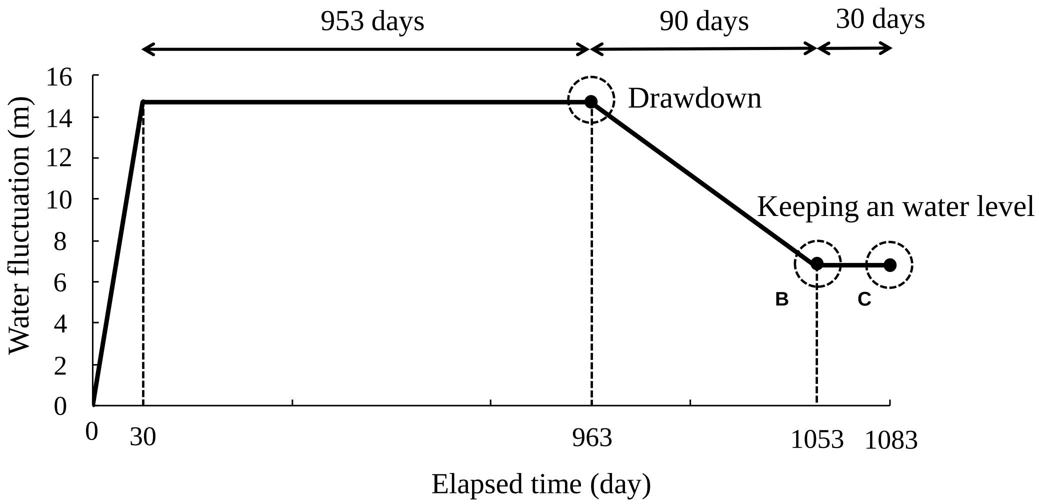


Figure 2.2 Condition of application for the water level in the upstream of reservoir

2.2.2 Ground parameters

Table 2.2 shows the input ground parameters used for the seepage flow analysis. The coefficient of permeability of the heightened materials (materials: core, embankment and filter) was provided by the Korean Rural Community Company (KRC)[4)]. In addition, the parameters used for the existing dam in this study were assumed in consideration of deterioration of an old fill-type dam.

The existing dam (Gyeryong reservoir) has existed for fifty years already and erosion of fine soil grains over time is expected to change the coefficient of permeability for each material. Accordingly, the average coefficients of permeability value of existing embankment (silt and sand) in four Korea reservoir dams[5)] having a lower permeability than that of heightened embankment was used.

Table 2.2 Ground parameters used for the seepage flow analysis

Materials	Soil-water characteristics under unsaterated condition				
	Coefficientof permeability k (m/s)	Voulumetric water content θ_r	Saturated water content θ_s	α (1/m)	n
Existing EMB	1.57E-06	0.221	0.565	1.470	6.656
Heightened EMB	5.75E-07	0.221	0.565	1.470	6.656
Existing core	1.14E-07	0.078	0.535	4.760	1.248
Heightened core	3.11E-08	0.078	0.535	4.760	1.248
Existing filter	1.00E-05	0.000	0.365	5.478	1.629
Heightened filter	5.45E-05	0.000	0.365	5.748	1.629
Foundation ground	5.00E-11	0.078	0.535	4.760	1.248

*EMB (Embankment): silt and sand
*Core: clay and silt
*Filter: sand

For the existing core (clay and silt), the coefficient of the permeability of the core changed according to the time based on the study[6] of core aging was applied.
For the existing filter (sand), the minimum value presented in the Casa Grande's Permeability Table[7] was cited as the filter performance was expected to be reduced due to the mixing between core and filter over time.

2.3 Piping Inspection and Seepage Characteristics by expanded structural core

2.3.1 Safety for piping inspection

The piping phenomenon has been discussed on the impaction to the safety of the fill-type dam due to their own materials characteristics. With regard to this matter if the existing dam is old, a leakage paths inside the dam body may exist, and this is likely to show different patterns from those obtained through analytic results since the passage of the time did not considered. Thus, the piping consideration has an importance as means of estimating the safety of the heightened dam. Figure 2.3 illustrates the evaluation location for hydraulic gradient at the range of the downstream slope and allowable seepage quantity that passes through the dam body at the central axis of the dam, and it was calculated considering the entire dam length 300m that has a relatively consistent shape as shown in Figure 2.4
As a analysis results, the seepage quantity per day that passes through the entire length of dam (300 m) is 57.70 m^3/day (Case1), which is within the range of 2,359 m^3/d, which is the safety management standard[8] for the allowable seepage quantity for total storage (0.05 percent of total storage); similarly the seepage quantity is 55.50 m^3/d (Case2), 53.90 m^3/d (Case3), and 50.50 m^3/d (Case4), which comes also satisfyingly within the safety management standard, which makes it judged to be safe.
Meanwhile, the hydraulic gradient revealed a decrease of approximately 0.25 in Cases 1 and Case 2, 0.23 in Case 3, and 0.22 in Case 4. Given that the piping safety standard of 0.5[9] was satisfied in all cases. Table 2.3 presents the result obtained in seepage quantity and hydraulic gradient, its possibility of piping was judged to be low. This is the natural results but it has an importance that the vulnerable part can be structurally reinforced.

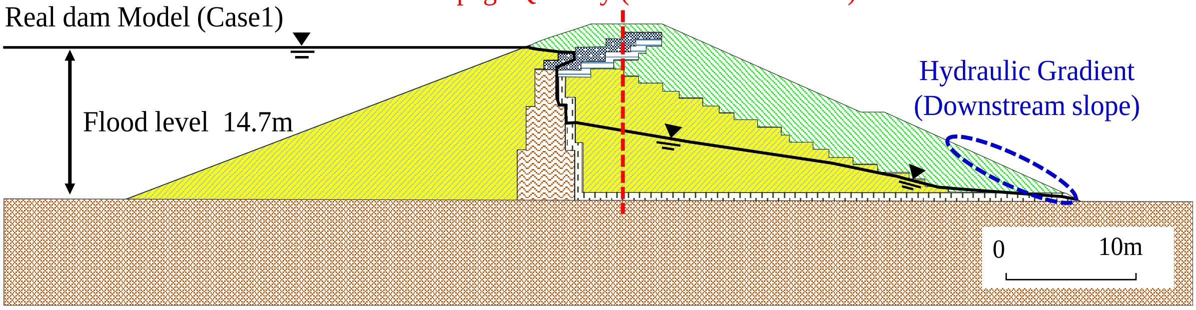


Figure 2.3 Evaluation location for hydraulic gradient and seepage quantity

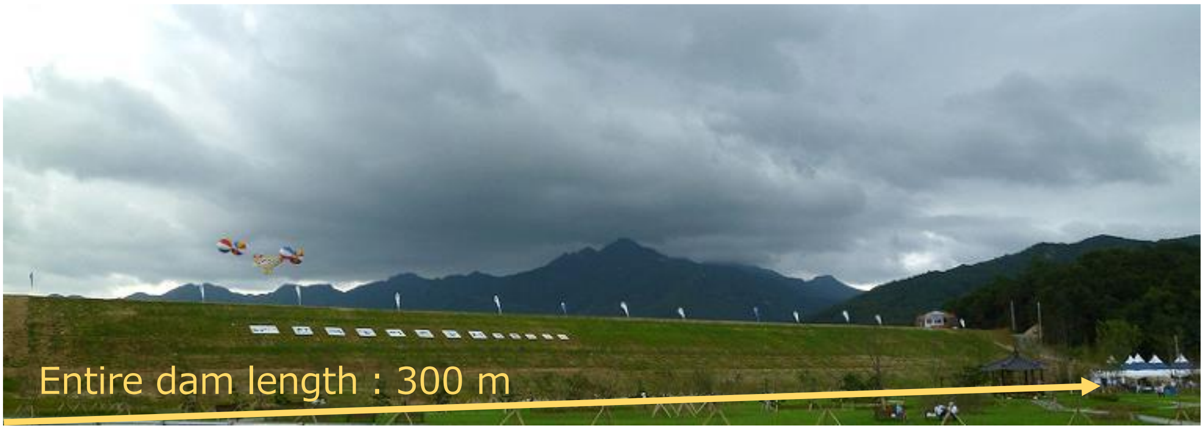


Figure 2.4 End of the dam in downstream-side (Gyeryong reservoir,2011.7)

Table 2.3 Result obtained in seepage quantity and hydraulic gradient

Division	Central axis	Downstream slope
	Seepage Quantity (m^3/s)	Hydraulic Gradient
Case1	57.7	0.25
Case2	55.5	0.25
Case3	53.9	0.23
Case4	50.5	0.22

2.3.2 Change of seepage line by expanded structural core

A seepage line is defined in a boundary line that is divided into the saturated zone and none-saturated zone. In general, checking the change of seepage line is related to the piping inspection, and it provides the state information inside of the dam body. With regard to this study, the change of seepage line according to the expanded structural core was evaluated to understand an impact on the core heightened dam for inclined-type. Figure 2.5-8 shows the change in seepage line according to the result of seepage flow analysis for each case. The result of analysis shows that Case 1 had the highest level with 7.28m and Case 4 had the lowest level with 6.86m. Due to the increased scale of the expanded core, the height of the seepage line in the downstream was a difference of about 0.4m between highest one and lowest one. The results are outlined in Table 2.4.

As a result, decrease of the height of seepage line has an effect to reduce the erosion phenomenon that can be caused by infiltration. Here the differences of the height of seepage line of each Case (Case1-4) was appeared to be a small, but the possibility of the breach failure (Concentration leak that occurred in the zone where the shear stress is low) is expect to be reduced largely when the entire dam length 300m is considered.

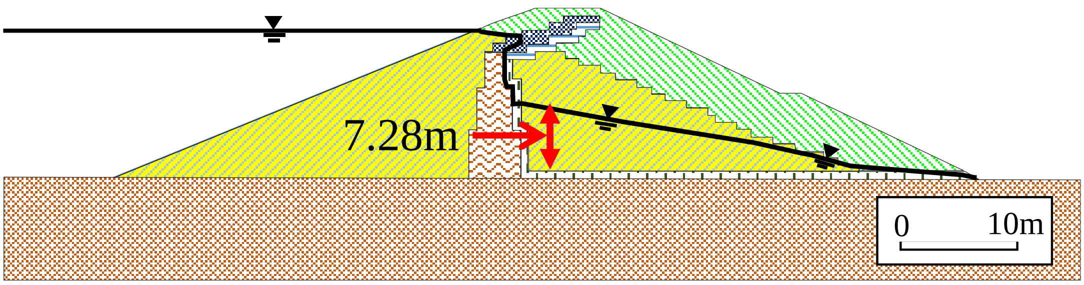


Figure 2.5 Change of seepage line in the model of Case 1

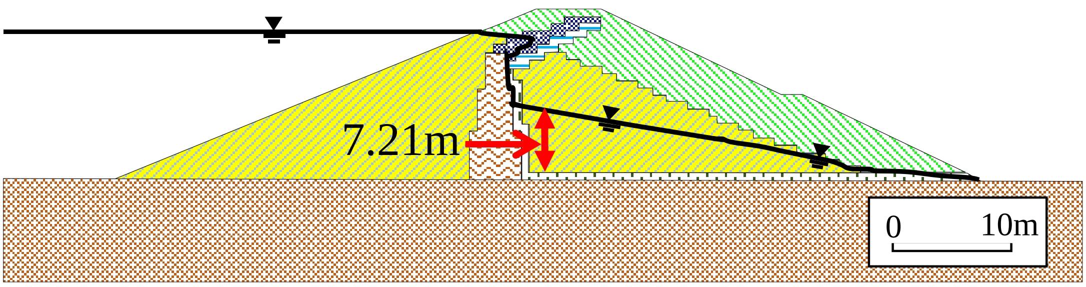


Figure 2.6 Change of seepage line in the model of Case 2

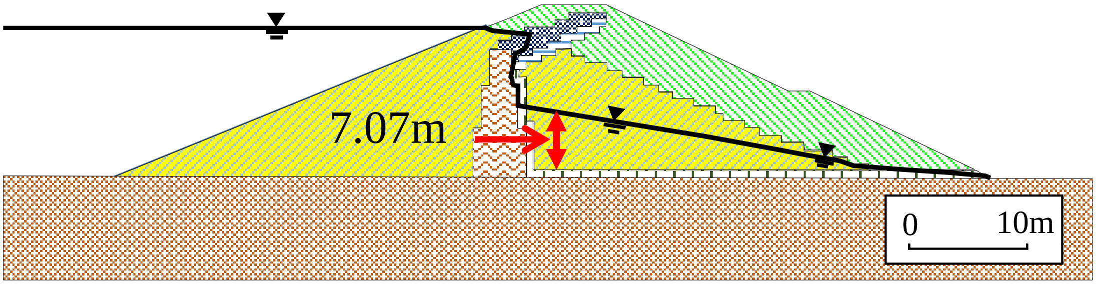


Figure 2.7 Change of seepage line in the model of Case 3

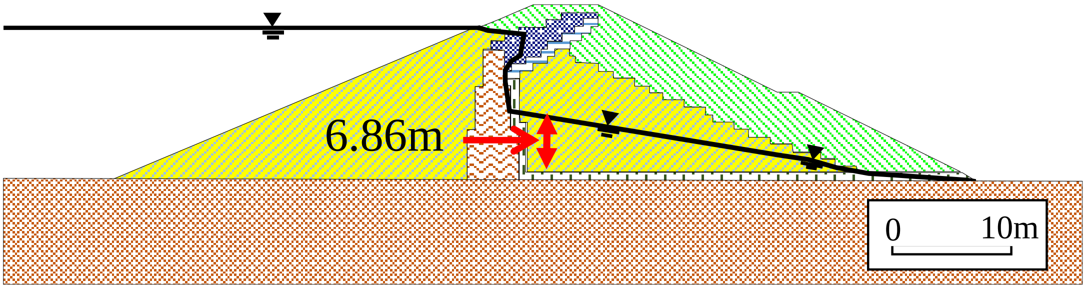


Figure 2.8 Change of seepage line in the model of Case 4

Table 2.4 Height of seepage line according to the expanded core scale

Case No.	Enlarged core scale	Height of seepage line
Case 1	11.76 m^2	7.28 m
Case 2	13.72 m^2	7.21 m
Case 3	17.15 m^2	7.07 m
Case 4	21.07 m^2	6.86 m

2.3.3 Shape of seepage line by expanded structural core

With section 2.4.2, the consideration of the seepage line in each case revealed that in all four cases, the seepage line shape presented overhanging shapes in the expanded cores, as shown in Figure 2.5; these shapes represent asymmetric formations, in contrast to the shape of the seepage line in common vertical cores. Here, the seepage line shape can influence the dam safety in relation to core crack and deformation at the core joint.

Once the crack or deformation that occurred in the core joint can make an increase of the seepage quantity, the inclined shape of the seepage line may be changed steadily to the vertical shape by gravity. This is related to a filter (sand) width to drainage the seepage water, and it is affected by flow velocity at the core joint, and seepage quantity through heightened core.

In connection with the analysis result, the inclined shape of the seepage line is approaching to the vertical shape as the expanded core scale get bigger, as shown in Figure 2.9-12.

Thus the expanded core scale in a core heightened dam for inclined-type is expected to be a stabilized with respect to control of the seepage line.

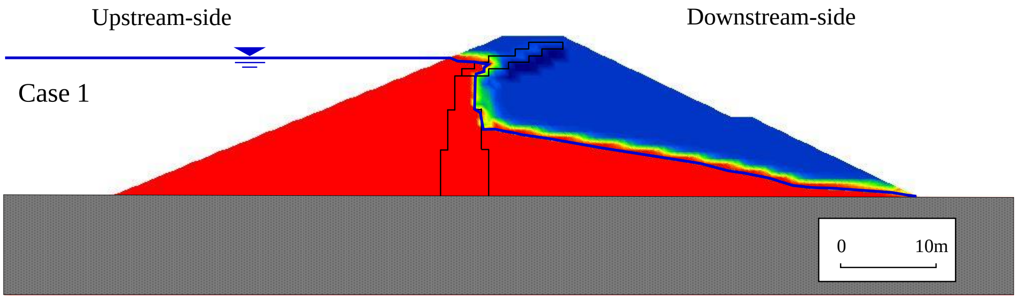
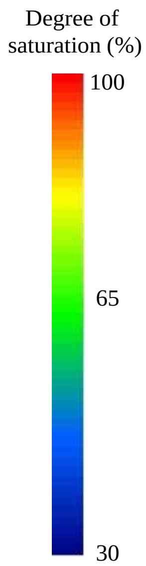


Figure 2.9 Shape of seepage line in the model of Case 1



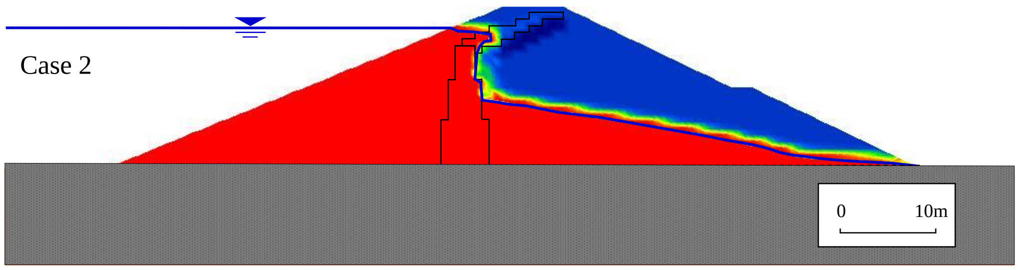


Figure 2.10 Shape of seepage line in the model of Case 2

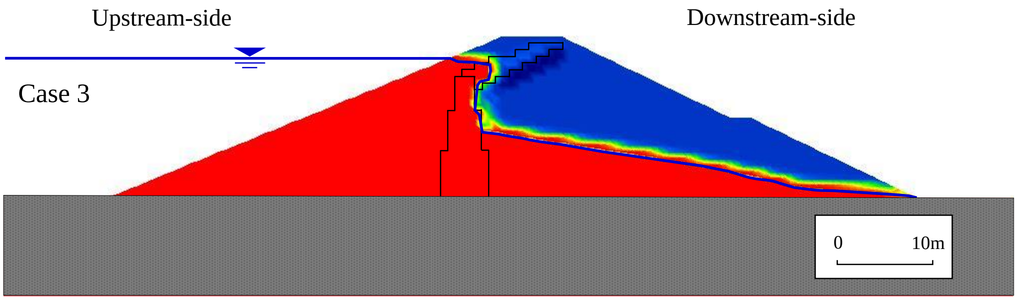


Figure 2.11 Shape of seepage line in the model of Case 3

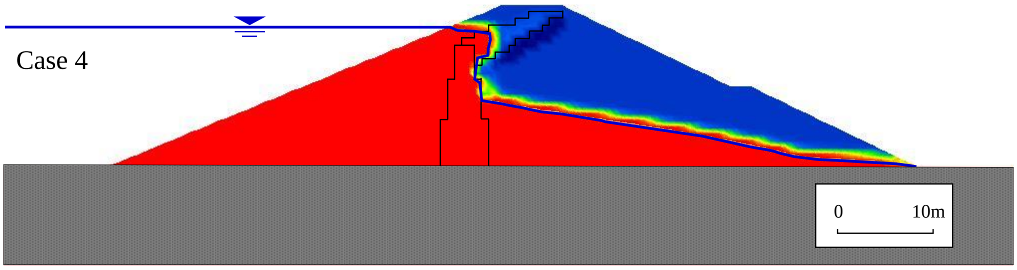
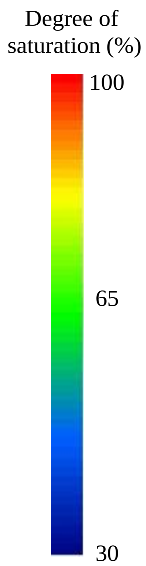


Figure 2.12 Shape of seepage line in the model of Case 4



2.3.4 Expanded effects of structural core on flow velocity and seepage quantity

This section contains the flow velocity at the core joint and the seepage quantity through the heightened core for inclined-type based on section 4.4.2. The core joint which is vulnerable part on permeable and dynamic behaviors as mentioned in chapter 1 and may cause the concentrated leak along with the boundary layer of the core. With regard to this, the erosion quantity of a soil particle due to the concentrated leak by time elapsed is increased, the flow velocity at the core joint get bigger. Thus, in this section, the expanding effects of the core were considered in details as flow velocity at the core joint, the change of seepage quantity that through the heightened core for inclined type. Figure 2.13 shows the model of Case 1, and Figure 2.14 illustrates the focused location for evaluating the flow velocity at the core joints and the seepage quantity from the upper center of the existing core to the upper center of the expanded core (approximately length 10 m), with reference to Case 1.

As the analysis result, with respect to Case 1 (flow velocity: 6.72 $\times 10^{-8}$ m/s), the decreased in the flow velocity was 1.06 times (Case2: 6.34 $\times 10^{-8}$ m/s), 1.50 times (Case3: 4.48 $\times 10^{-8}$ m/s), and 1.77 times (Case4: 3.81 $\times 10^{-8}$ m/s), respectively.

In the heightened core (inclined core), with respect to Case 1 (seepage quantity: 9.61 $\times 10^{-8}$ m^3/s), the decrease in seepage quantity was 1.07 times (Case 2: 8.94 $\times 10^{-8}$ m^3/s), 1.31 times (Case 3: 7.31 $\times 10^{-8}$ m^3/s), and 1.52 times (Case 4: 6.32 $\times 10^{-8}$ m^3/s) respectively. The all results are outlined in Table 2.5. These results (flow velocity and seepage quantity) are closely associated with the increase of the back water distance of the core that controls the seepage water, and thus it is expect to have an importance as means of the reduction of soil erosion velocity in relation to the narrow core width (1.5-3m) of a reservoir. However, there could be a more evaluation about what they mean in terms of engineering, with regard to the erosion in core joint.

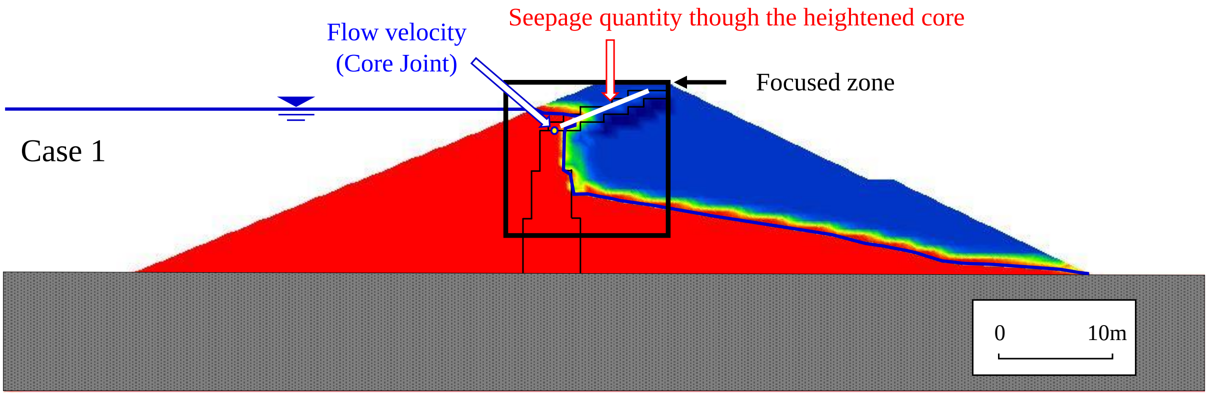


Figure 2.13 Focused zone for evaluating the core joint and the seepage quantity

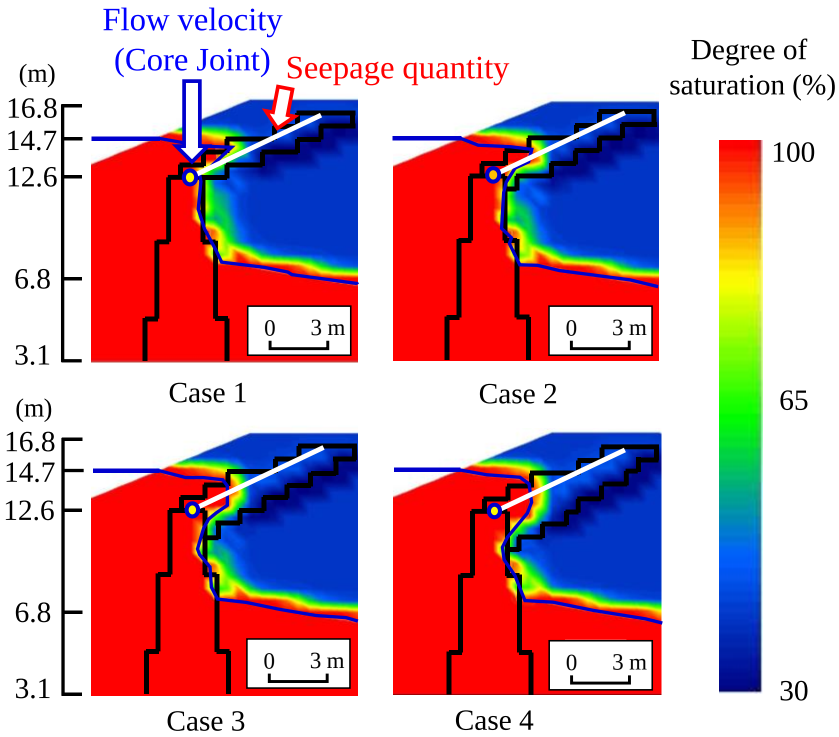


Figure 2.14 Focused location for seepage quantity and flow velocity

Table 2.5 Result of value for seepage quantity and flow velocity

Division	Heightened core	Core joint
	Seepage quantity (m^3/s)	Flow velocity (m/s)
Case 1	9.61×10^{-8}	6.72×10^{-8}
Case 2	8.94×10^{-8}	6.34×10^{-8}
Case 3	7.31×10^{-8}	4.48×10^{-8}
Case 4	6.32×10^{-8}	3.81×10^{-8}

2.3.5 Saturation characteristics of the core under the conditions of water drawdown

Figure 2.15 shows the saturation state of the core after the water level decreased was maintained constant for about 30 days following the drawdown of water level from the flood level (14.7 m) to the low level (6.8 m).

The saturation of the expanded core was found to be higher than the pre-expansion core, and the moisture-retaining area increased in proportion to the scale of the core. This may be explained by the deceleration of the seepage water drainage via filter due to the increased flow line gradient inside the inclined core as a result of the increased back water distance, as shown in Figure 2.16. In addition, the scope of residual saturation area shown in the model representing Case 1-4 was demonstrated more clearly in the Case 2-4 model, in which the influence exerted on the core joint increases as the saturation zone increases.

In contrast, the saturation of Case 1 model was estimated to be lower (55–75%) than that of Case 2-4 model, as shown in Zone A of the core that stretches obliquely from the core joint, as shown in Figure 2.15. The low saturation in Zone A can be ascribed to the reduced back water distance because of the narrow core width. By its very design, this Zone A has a relatively high water permeability under seepage conditions. This also means that in case of a prolonged dry period, i.e., under drawdown conditions, the core can turn into a plastic zone over time, and become prone to earthquake-induced cracks or deformation. This can be explained by the fact that a low-saturation material has greater vulnerability to shear deformation than a high-saturation material[10)], as shown in Figure 2.17.

Consequently, when a reservoir dam is built in a hydrodynamic zone, possible damages due to cracks and deformation of the core can be reduced by a greater degree as the scope of residual moisture zone in the expanded structural core. This is expected to have reinforcing effects and can thus contribute to the enhancement of the seismic performance of a core heightened dam for inclined-type.

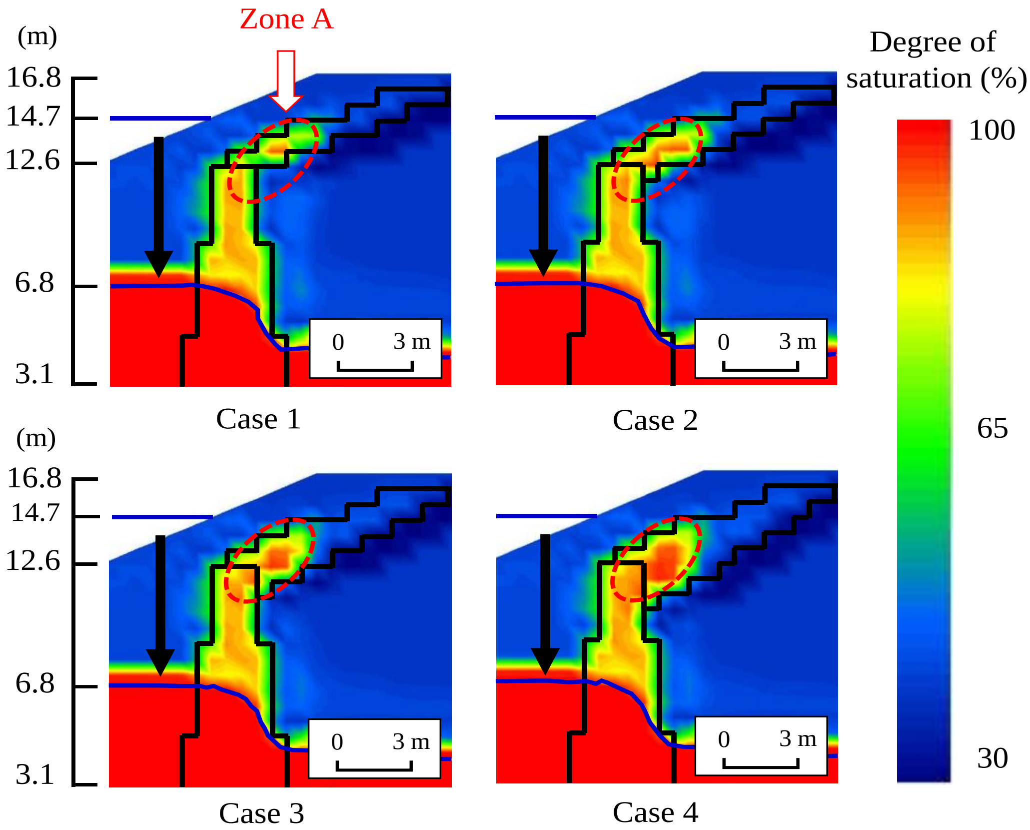


Figure 2.15 Saturation state of the core after the water level decreased

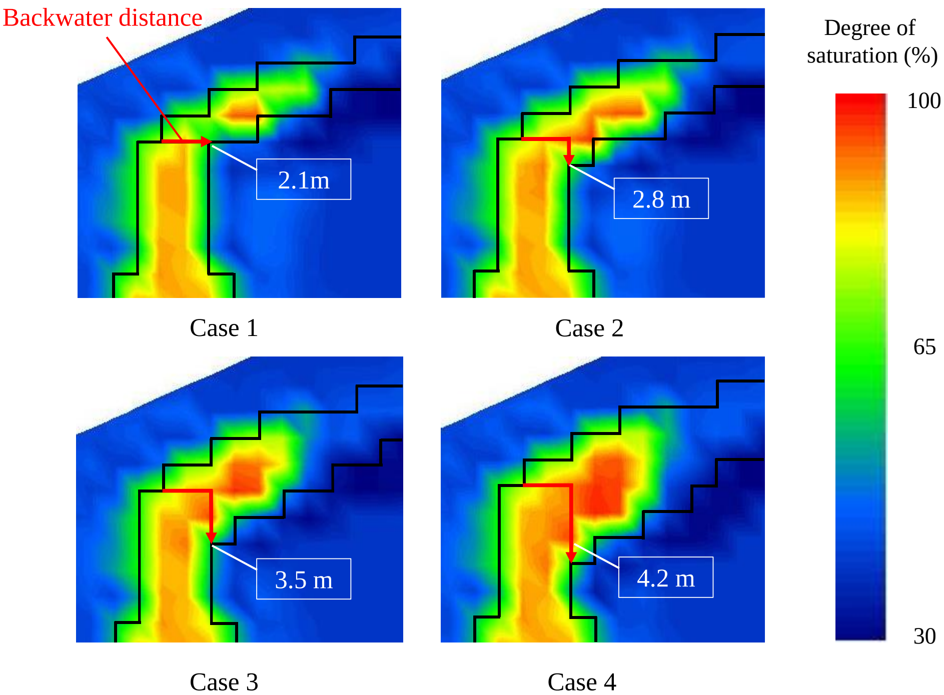


Figure 2.16 Estimated backwater distance of the core in each Case

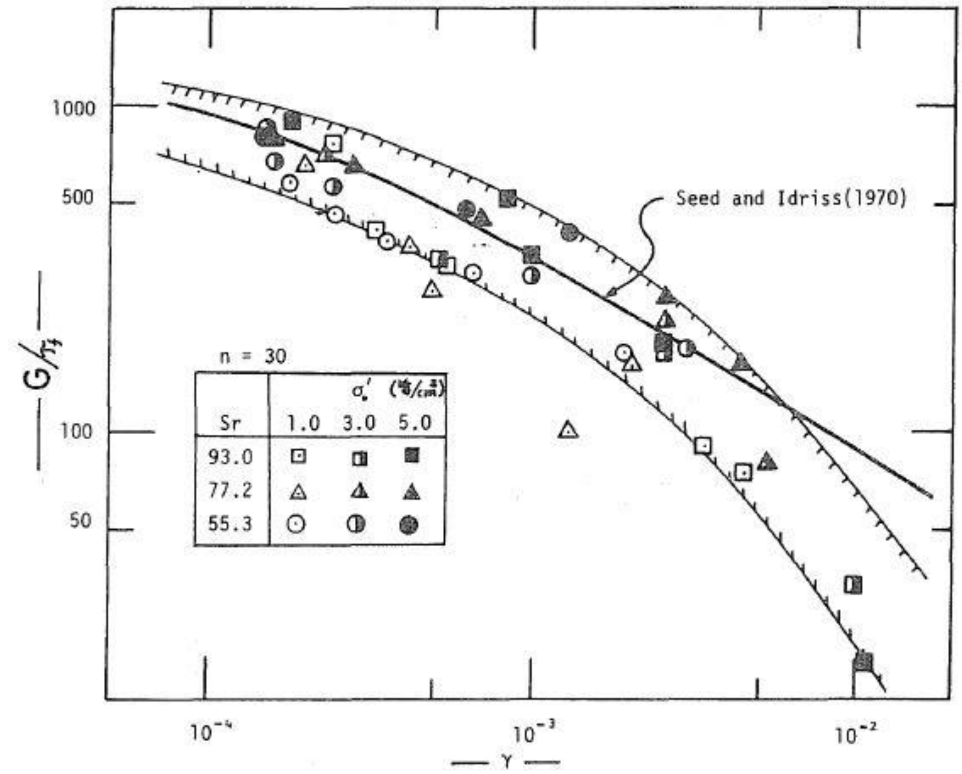


Figure 2.17 Example on the relation between shear modulus and shear strain affected by saturation ratio[10)]

2.4 Design range of the coefficient of permeability for heightened core

This chapter discusses the design range of the coefficient of permeability for the heightened core as an important factor for reducing the construction cost and enhancing the work efficiency. The generally known upper limit of the design range of the coefficient of permeability for a dam core is allowable up to 1.0-9.9×10^{-7} m/s. The coefficient of permeability of soil is closely associated with the structural composition (clay and silt) and the compressibility of the soil, which has a great impact on the construction cost and work efficiency.

In this study, the main focus was laid on the expansion of the range of coefficient of permeability as a strategy for reducing construction cost and improving construction efficiency. The following is the rationale behind opting for the expansion of the range of the coefficient of permeability.

(1) The zone for the heightened core is located in the upper part of the reservoir and thus exposed to relatively lower hydrostatic pressure compared to the existing core.

(2) A slight increase in the design coefficient of permeability of the heightened core, if implemented within the permissible level of seepage quantity (0.05% of the reservoir capacity), has a negligible impact on the dam safety.

As described above, since the change in the coefficient of permeability for the heightened core (k_{new}) hardly affects the reservoir dam safety, it can be designed in a manner to enhance the efficiency related to the construction cost and work process.

To investigate the feasibility of this strategy, the coefficient of permeability for the heightened core was varied by applying 0.3, 0.5, 1, 5, 10, 20, 40, 60, and 80 times of the coefficient of permeability (k_{old}) for the existing core of the Gyeryong reservoir, as displayed in Table 1, whereby the latter was configured to have a constant value (k_{old}: 1.14E-7 m/s), followed by FEM seepage analysis performed for each ratio. The coefficient of permeability for the existing core was configured to have a fixed value because a heightened core is constructed to address problems such as leakage or seepage and thus may have a lower coefficient of permeability compared to that of the existing core (for example, the coefficient of permeability for the heightened core of the Gyeryong reservoir has a design value smaller than that of the existing core). Tables 2.6 and 2.7 present the application conditions and results of the seepage analysis of Cases 1 and 4, respectively, according to the expanded scale of the core. The seepage quantity as per each ratio determined by the seepage analysis was normalized with respect to the coefficient of permeability for the existing core.

Table 2.6 Seepage analysis application conditions and results in the model of Case 1

Case 1	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9
k_{new} (m/s)	3.11E-8	5.70E-8	1.14E-7	5.70E-7	1.14E-6	2.28E-6	4.56E-6	6.84E-6	9.12E-6
k_{old} (m/s)	1.14E-7	1.10E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7
Ratio $\frac{k_{new}}{k_{old}}$	0.3	0.5	1	5	10	20	40	60	80
Seepage quantity (m^3/d)	58.76	59.07	59.82	63.66	65.19	66.67	68.40	69.52	70.58
Normalization	0.98	0.99	1.00	1.06	1.09	1.11	1.14	1.16	1.18

$*$ k_{new} : Coefficient of permeability for heightened core

$*$ k_{old} : Coefficient of permeability for existing core

Table 2.7 Seepage analysis application conditions and results in the model of Case 4

Case 4	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9
k_{new} (m/s)	3.11E-8	5.70E-8	1.14E-7	5.70E-7	1.14E-6	2.28E-6	4.56E-6	6.84E-6	9.12E-6
k_{old} (m/s)	1.14E-7	1.10E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7	1.14E-7
Ratio $\frac{k_{new}}{k_{old}}$	0.3	0.5	1	5	10	20	40	60	80
Seepage quantity (m^3/d)	54.11	54.62	55.07	57.11	58.58	59.31	59.80	60.68	60.91
Normalization	0.98	0.99	1.00	1.04	1.06	1.08	1.09	1.10	1.11

Figures 2.18 and 2.19 illustrate the results of the normalization according to the ratio of the coefficient of permeability for the heightened core to that for the existing core (k_{new}/k_{old}). The range covering Types 1-3 in Figures 2.18 and 2.19 denotes the available coefficients of permeability, whereas the range covering Types 4–8 denotes the target coefficients of permeability considering the allowable limit of water leakage comparing with that of the existing dam whose coefficient of permeability is designed generally to be smaller than the existing one, for example, 1.14E-7 m/s of Gyeryong reservoir. Hereupon, the allowable normalized value can estimate freely according to the required performance for the heightened dam planed within the permitted leakage water, for example, 0.05% of the reservoir capacity. When the normalized value of 1.10 is applied, the log curves of the seepage tendencies of Types 4–8 in Figures 2.18 and 2.19 can be used. From the resultant values, it was verified that the target coefficients of permeability (normalized value: 1.10) relative to the upper limit of available coefficients of permeability have the ranges up to 1.43E-6 and 6.70E-6 m/s for Cases 1 and 4, respectively. Furthermore, comparing the coefficients of permeability for Cases 1 and 4 as obtained from the log curves, Case 4 demonstrated a 4.68-fold increase potential of that of Case 1.

From this finding, it can be inferred that the impact of the scale of the heightened core expanded at the core joint on the seepage quantity within the reservoir is relatively strong under the conditions with changed coefficient of permeability for the heightened core.

In consequence of the analysis results presented in this section, the area for borrow pit around the reservoir available for core construction may be expanded in future heightening construction projects of a reservoir due to the quality conditions for the core-building soil slightly inferior to the current standards as a result of the increase in coefficient of permeability for the heightened core. Moreover, construction period for core expansion may be reduced and the construction efficiency enhanced through the reduced use of core soil compaction equipment (rollers).

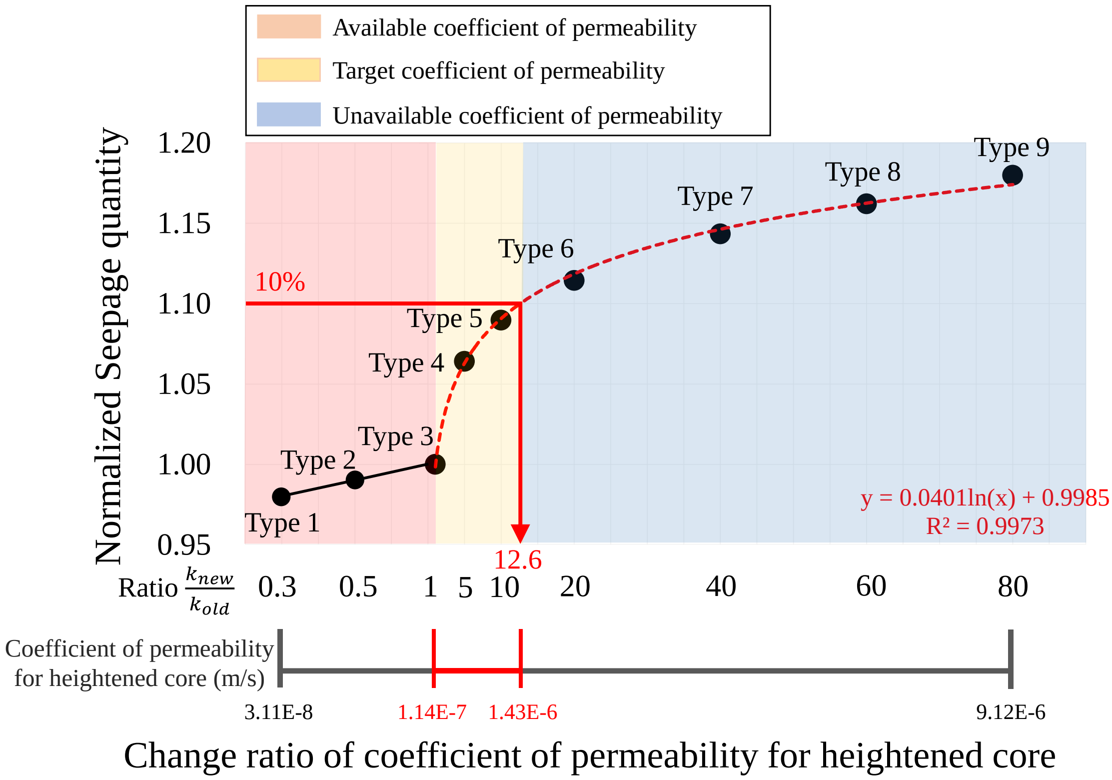


Figure 2.18 Results of the normalization according to the ratio of the coefficient of permeability for the heightened core to that for the existing core (k_{new}/k_{old}) in Case 1.

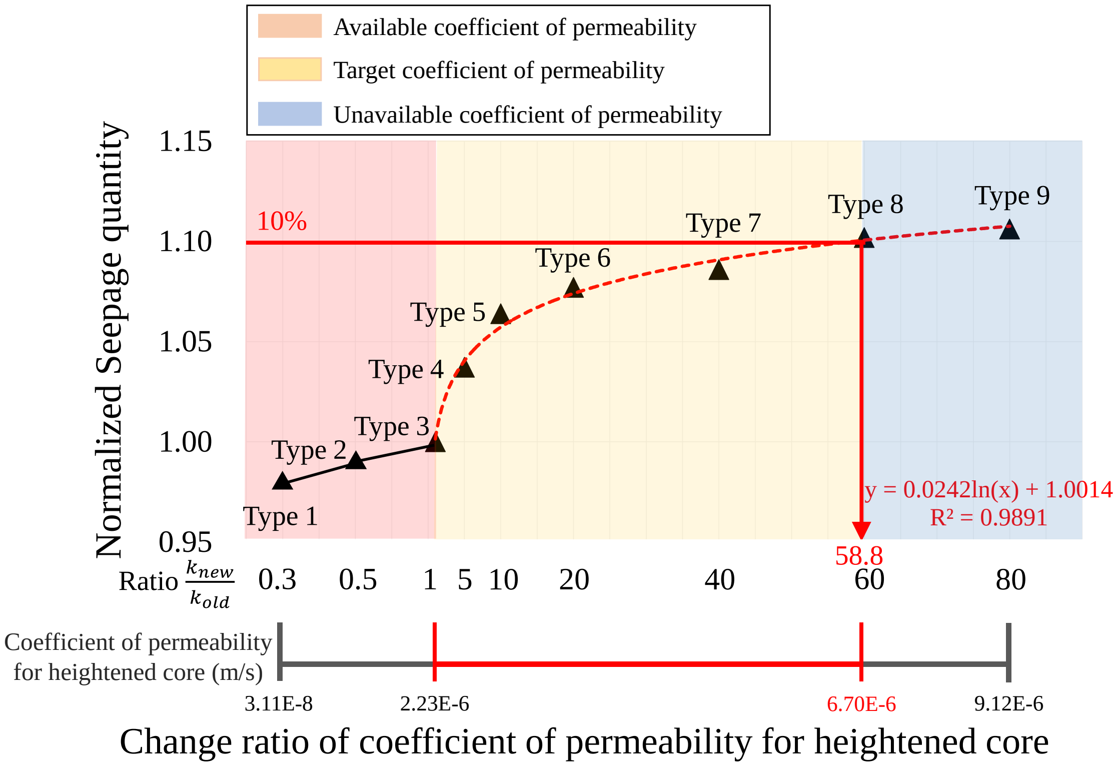


Figure 2.19 Results of the normalization according to the ratio of the coefficient of permeability for the heightened core to that for the existing core (k_{new}/k_{old}) in Case 4.

2.5 Summary

In this chapter, the study was performed to investigate the expanded effects of core joint on the seepage characteristics of a core heightened dam by inclined-type. The seepage flow analysis was analyzed for its four kinds of the scale structures of cores and the followings are the summary.

(1) Regarding the influence of the expanded scale (each case) of core joint structures; the piping on the downstream slope revealed that piping safety standards were met in all the cases investigated in this study, and thus, the risk of core expansion-induced piping is extremely low.

(2) The seepage line of downstream dam body decreased gradually as the scale of the expanded structural cores increased at downstream, the height of the seepage line shows the reduction effect of 1m between the highest one and the lowest one. As the reduction of seepage line in downstream is connected to a collapse of downstream slope caused by the piping, this can contribute to keeping the safety of heightened dam.

(3) In relation to the result of piping consideration, a core joint can be reinforced by core expansion of an inclined-type dam owing to the decrease in the quantity of seepage passing through the inclined-type core and the flow velocity at the core joint.

(4) Under drawdown up to low water level, the increase of the zone containing residual moisture through the expansion of the core scale is expected to have reinforcing effects in the reduction of possible damages associated with cracks or deformation of the core, thus enhancing the seismic performance of a heightened dam.

(5) In the design value of the coefficient of permeability for the heightened core investigated in this study, it can be alleviated through the required performance for the heightened dam planed within the allowable leakage water. Thus, it is expect to improve the heightening work efficiency, since the area for borrow pit around the reservoir available for core construction are wide.

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Chapter 3

3. Expanding Effects of Structural Core on Dynamic Performance of the Heightened Reservoir Dam

In this chapter, the expanding effects of structural core on dynamic performance of the heightened reservoir dam are discussed by using FEM dynamic analysis method. As mentioned in chapter 1, as the crack and deformation are associated with the piping problem caused by concentrated leak from upstream-side of the reservoir, the consideration of the expanding effects at the core joint has importance as means of the decrease of the potential crack and deformation. In connection with this, the dynamic effective stress analysis UWLC program[1)] was used to evaluate the dynamic response in the core heightened dam for inclined-type. In regard to this, the modified Ramberg-Osgood model[2)], which can consider the attenuation deformation change or the shearing force stiffness, was applied to the dam body, and the elastic model was applied to the foundation ground. In addition, seepage lines obtained from the seepage flow analysis (In chapter 2) for each model were applied to the dynamic analysis model.

3.1 Conditions of Application for Dynamic Response Analysis

3.1.1 Boundary condition

In the boundary conditions of the initial stress analysis, the foundation bottom was set as a fixed point, and both sides wall were set as support points for the vertical roller. In the dynamic analysis, the foundation bottom and the side walls were set to the viscosity boundary. Meanwhile, natural frequency and dynamic response of the structure on the ground is significantly varies if it is related to the flow of water. The reason for this is that the water pressure acting on the structure causing the infiltration and the resulting structure is subjected to the hydrodynamic. Therefore, in order to analyze accurately the specific behavior or dynamic response of the structure in contact with water should reflect the hydrodynamic effects. In regard to this, Westergaard's added mass method[3)] was applied to the hydrodynamic pressure, which was set to act on each point of the upstream slope.

Here, the added mass is a method for applying the mass to the structure after the dynamic effect of water is converted to the mass. If it applied to the analytical cross section, the analysis technique may be simplified. The hydrodynamic pressure used in finite element method (FEM) analysis is shown as Eq. 3.1.

$$m_v = \frac{7}{8}\sqrt{h(h-y)} \quad \text{Eq.3.1}$$

Here, m_v: Hydrodynamic pressure
h: Depth from full level to foundation ground
y: Depth from full level to random dot

3.1.2 Ground parameters

Table 3.1 shows the ground parameters used for the dynamic analysis. The parameters used for before and after heightening construction on the angle of internal friction, cohesion, and wet unit weight were the same as those applied to the evaluation of slope stability of the Gyeryong reservoir based on the data[4)] collected by the Korea Rural Community Corp (KRC).

For Poisson's ratio, the data was cited in previous study[5)] on evaluation of seepage stability for the heightened dam of Gyeryong reservoir. As for shear wave velocity and Young's modulus[6)], it were cited data obtained from the Comaba reservoir dam in Japan, whose scale, type, and dam height are similar to that of Gyeryong reservoir dam. In addition, nonlinear dynamic deformation characteristics (G/G0, h-γ curve) of each material were applied based on the seismic observation record of the fill-type dam in Japan.

Table 3.1 Ground parameters used for the dynamic analysis

Materials	Cohesion (kPa)	Angle of internal friction (deg.)	Unit weight (kN/m^3)	Saturated unit weight (kN/m^3)	Poisson's ratio	Young's modulus (kPa)	Model
Existing EMB	31.00	30	19.70	21.02	0.35	2.46E+05	Modified R-O model
Heightened EMB	16.70	24	18.25	19.42	0.35	2.46E+05	
Existing core	26.00	12	19.28	21.38	0.45	2.20E+05	
Heightened core	34.30	9	17.65	19.57	0.45	2.20E+05	
Existing filter	0.00	33	18.63	19.63	0.33	2.46E+05	
Heightened filter	0.00	33	18.63	19.63	0.33	2.46E+05	
Riprap	0.00	45	22.56	22.56	0.23	1.61E+06	
Foundation ground	18.19	35	20.62	22.00	0.30	6.00E+06	Elastic model

*EMB (Embankment): silt and sand
*Core: clay and silt
*Filter: sand

3.2 Dynamic Response Characteristics of the Expanded Structural Core by Input Sinusoidal Wave

3.2.1 Estimation of natural frequencies

The main cause to perform the natural frequency analysis is to find the natural frequency of the structure related to a resonance.

Here the natural frequency (f) is the representative concept, which is presented to the dynamic characteristics of the structure, and the natural period (T) is expressed to T=1/f with respect to the frequency. Here, the natural period is closely associated to the resonance of the dam structure, it may cause severe damages to the dam when the resonance last. Therefore, understanding the natural period of the dam structure is very crucial, and thus this study performed that it evaluated the natural frequency on impact of four kinds of model induced by the expanded scale of the structural core. For the evaluation of the natural period of the analysis model for the four cases, a horizontal excitation amplitude was applied by using a white noise which is a random signal with a constant power spectral density and refers to a statistical model for signals and signal sources, rather than to any specific signal[7)] as shown in Figure 3.1, and the natural frequency was measured with the transfer function of the dam foundation in relation to the dam crest. In regard to this, Figure 3.2 shows the location of the foundation and dam crest of the dam whose acceleration response spectrum was assessed and Figure 3.3 shows the results of the transfer function. As shown in Figure 3.3, a natural frequency of 6.2 Hz and a natural period of 0.16 seconds were measured in all cases. The results indicate that influence of the expanded scale of the structural core on the natural period of the dam was verified to be almost non-existent. In addition, according to the Okamoto empirical formula[8)] concerning the relationship between an earth-fill dam and the natural period, the natural period on height-dependent earth-fill dams is estimated to range from 0.024 (lowest) to 0.28 (highest) seconds in this dam height. The natural period of 0.16 seconds obtained in this analysis is within the range of the Okamoto empirical formula. Therefore, input sinusoidal waveform in this study is determined to be 0.16 seconds.

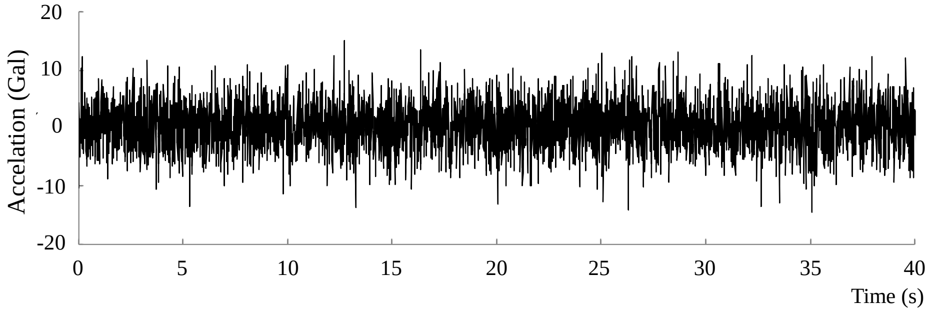


Figure 3.1 White noise waveform used for evaluating the natural period

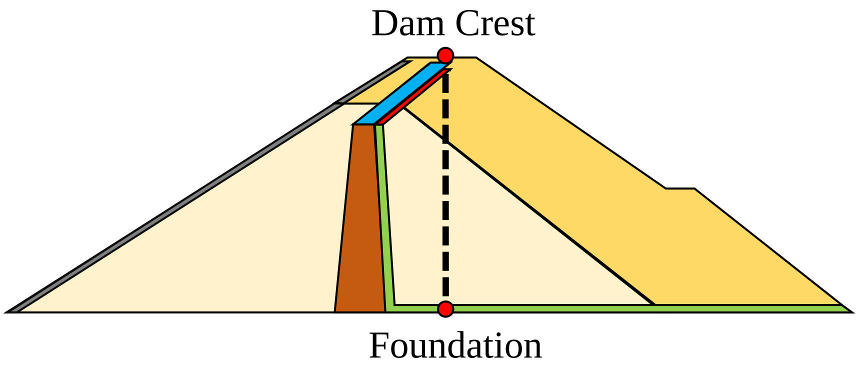


Figure 3.2 Evaluation location of acceleration response spectrum

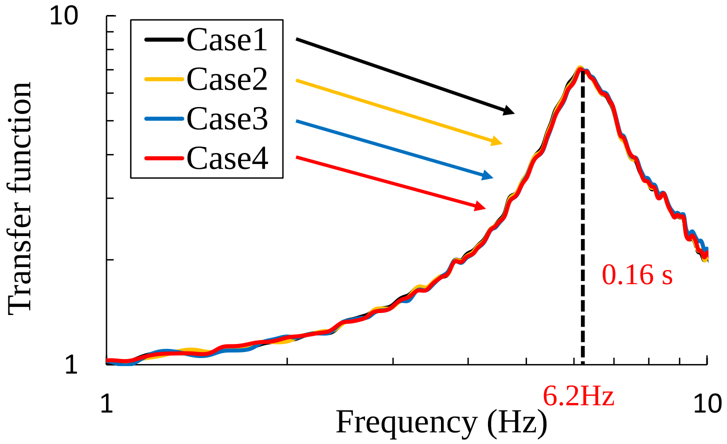


Figure 3.3 Results of the transfer function

3.2.2 Input sinusoidal waveform

Based on the result (natural period: 0.16 s) obtained in the natural frequency analysis, a sinusoidal waveform was formed. Here, since the sinusoidal waveform has the same maximum acceleration value and constant cycle on both positive and negative sine, the shape mode of the heightened dam according to the direction of dynamic response during excitation can be estimated. In regard to this, the core that is newly constructed is heightened to the downstream-side of the reservoir, and thus this study focused on the core joint zone to understand the differences according to the response direction on core deformation. Here, the input seismic coefficient direction must be defined prior to the dynamic response analysis to obtain a more-reliable results. In regard to this, a horizontal (front and the back side of the reservoir dam) and vertical directions for a seismic coefficient are generally used, and the consideration of the direction including the horizontal direction for right and left side of the reservoir are needed. In this study, the horizontal coefficient which is the biggest direction influencing the dam safety in relation to the heightened structural core was considered among those three type directions. The main reasons are as follow; first, the cross section placed in the upstream-side was under water and this may be a load with hydrodynamic pressure during an earthquake. Hereupon, the dynamic behavior acting on the heightened core by inclined-type can be bigger since the core is in tilted structure which is heightened to downstream-side. On the other hand, for a structures on reinforced ground (including the reservoir ground), the value of vertical seismic coefficient (k_V) is widely recognized as 0.5 k_H (k_H: horizontal seismic coefficient), the influence by an earthquake is expected to be lower than the horizontal direction. For the dynamic response by the horizontal direction for right and left side, it is expected to be lower than that of the horizontal direction of the front and the back side since each side of the wall in the dam was configured to have a fixed by wall-grout. As stated above, in the dynamic response analysis, the horizontal direction (front and the back side of the reservoir dam) for a seismic coefficient was considered.

Figure 3.4 shows the location of the input sinusoidal waveform. In connection to the maximum amplitude of input sinusoidal waveform, the design seismic coefficient of the area where Gyeryong reservoir was determined to be 0.1584 by the seismic design standard[9] was applied. Here, the relationship between the design horizontal seismic coefficient and the peak amplitude of acceleration is generally known to be influenced by the dynamic performance of a dam or the frequency of the input seismic motion. While, Noda's formula is generally used to determine this relationship, it can also be expressed by the product of the design seismic coefficient and the gravitational acceleration if the peak amplitude of acceleration is 200 Gal or less[10]. Moreover, in the case of the Gyeryong reservoir, if the value is obtained by converting k_H= 0.1584 using the inverse square law 1/3, the maximum acceleration can be

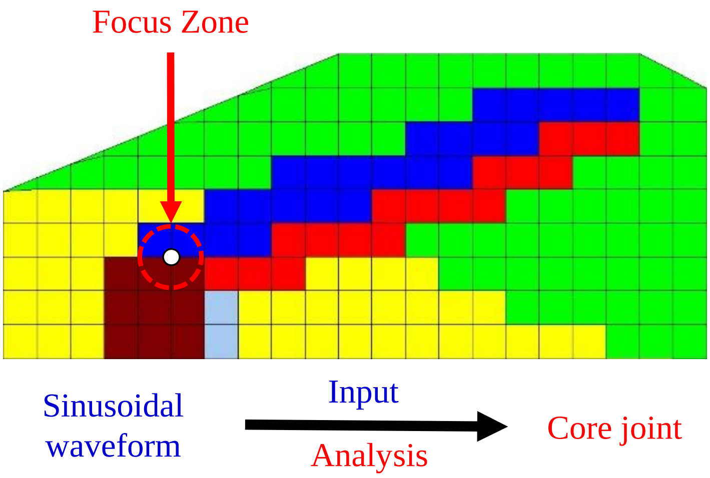


Figure 3.4 Location of the input sinusoidal waveform

underestimated as compared to the value obtained by simply multiplying the gravitational acceleration.

Therefore, in this study, a uniform maximum acceleration of 150 Gal was applied to all the input waveforms, and then the maximum shear stress acting on the core joint zone was analyzed. Figure 3.5 shows the shear stress, acceleration, and sinusoidal waveform based on the result of natural periods (0.16 seconds) of the heightened dam. In regard to this, the maximum shear stress were tracked for every one second from 0.88 to 1.04 second on the seventh waveforms having a stable state in the maximum amplitude of acceleration and evaluate the time section responded to the upstream (negative sine) and downstream (positive sine) direction of the reservoir. As results, the maximum shear stress of the dynamic response at the core join zone in the downstream was 0.96 seconds and that to the upstream direction was 0.88 seconds.

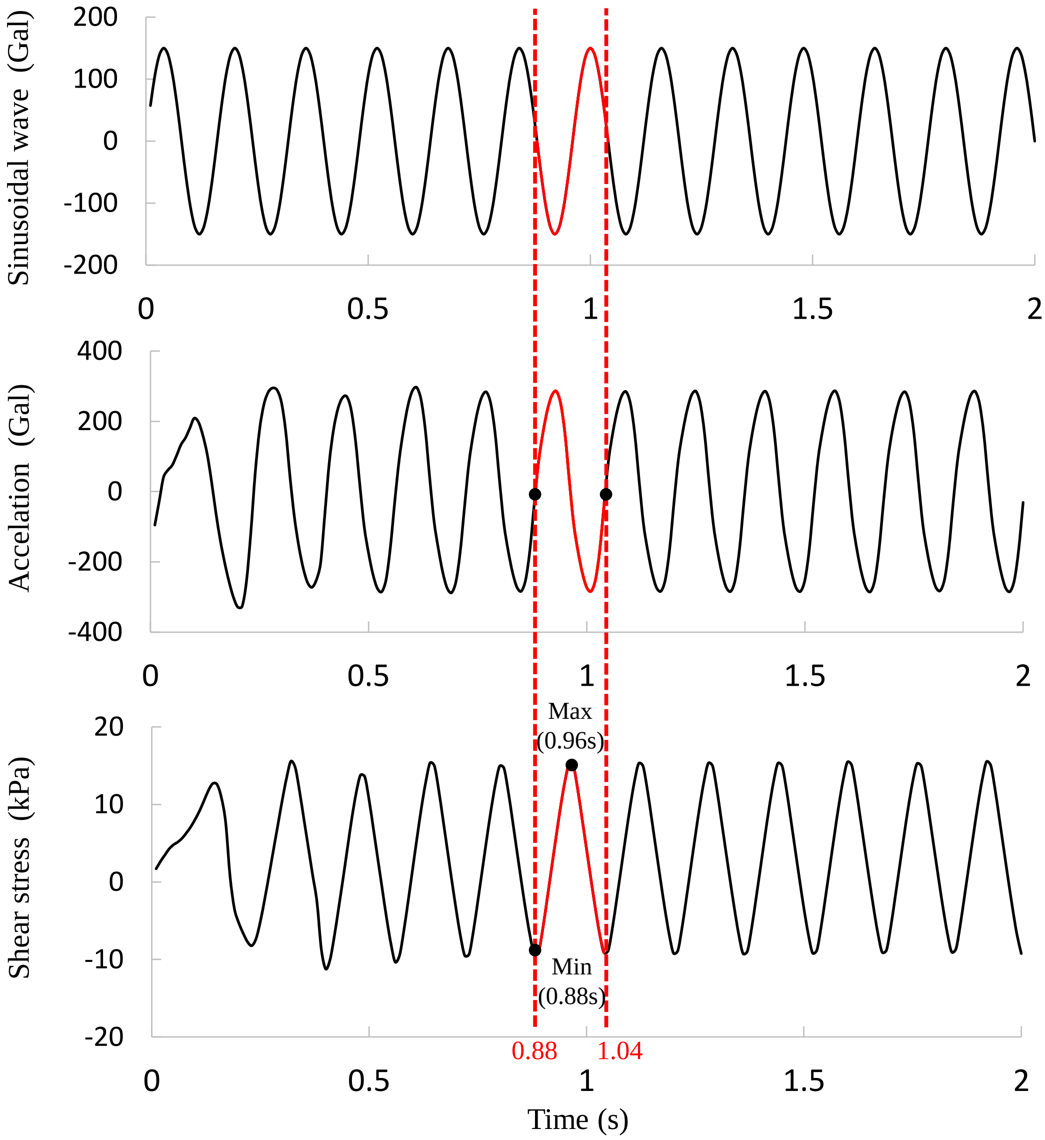


Figure 3.5 Shear stress, acceleration, and sinusoidal waveform based on the result of natural periods (0.16 seconds) of the core heightened dam by inclined-type

3.2.3 Results of dynamic response by input sinusoidal waveform

As in the asymmetrical inclined structural core, the dynamic response of the dam body may depend on the direction of the dynamic response. Accordingly, the dynamic response (shear stress) on the dam body of sinusoidal waveform (0.16 s) is firstly focused on the differences of the directions (upstream and downstream-side of the reservoir) during the earthquakes.

Figure 3.6 and 3.7 shows the result of the shear stress that occurred in the dam as a dynamic response to the direction of upstream and downstream-side of the reservoir.

The distribution of the shear stress that occurred in the focused zone (core joint) which the scale of core are changed was considered.

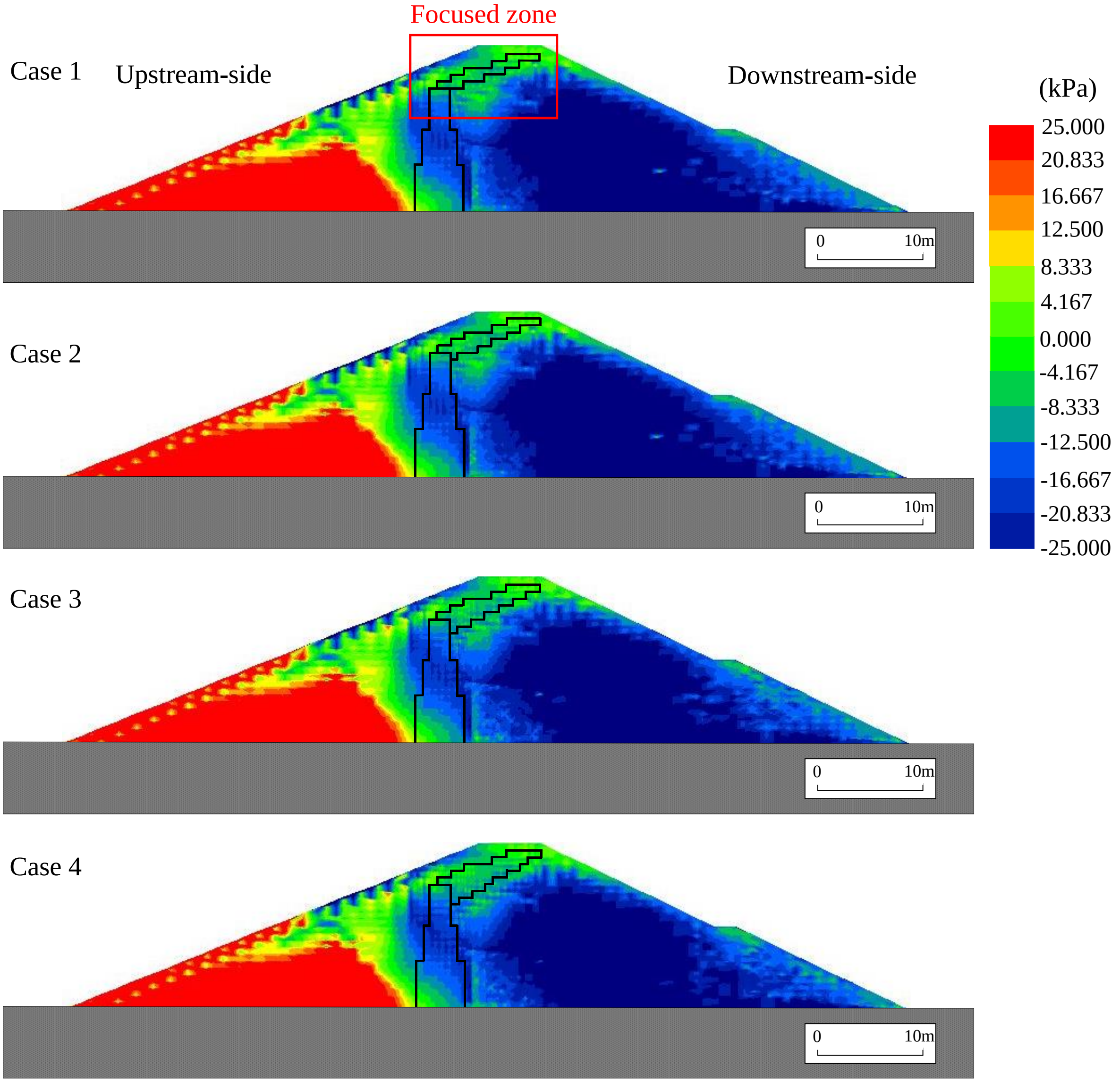


Figure 3.6 Result of the shear stress that occurred in the dam as a response to the direction of upstream-side (Case1-4)

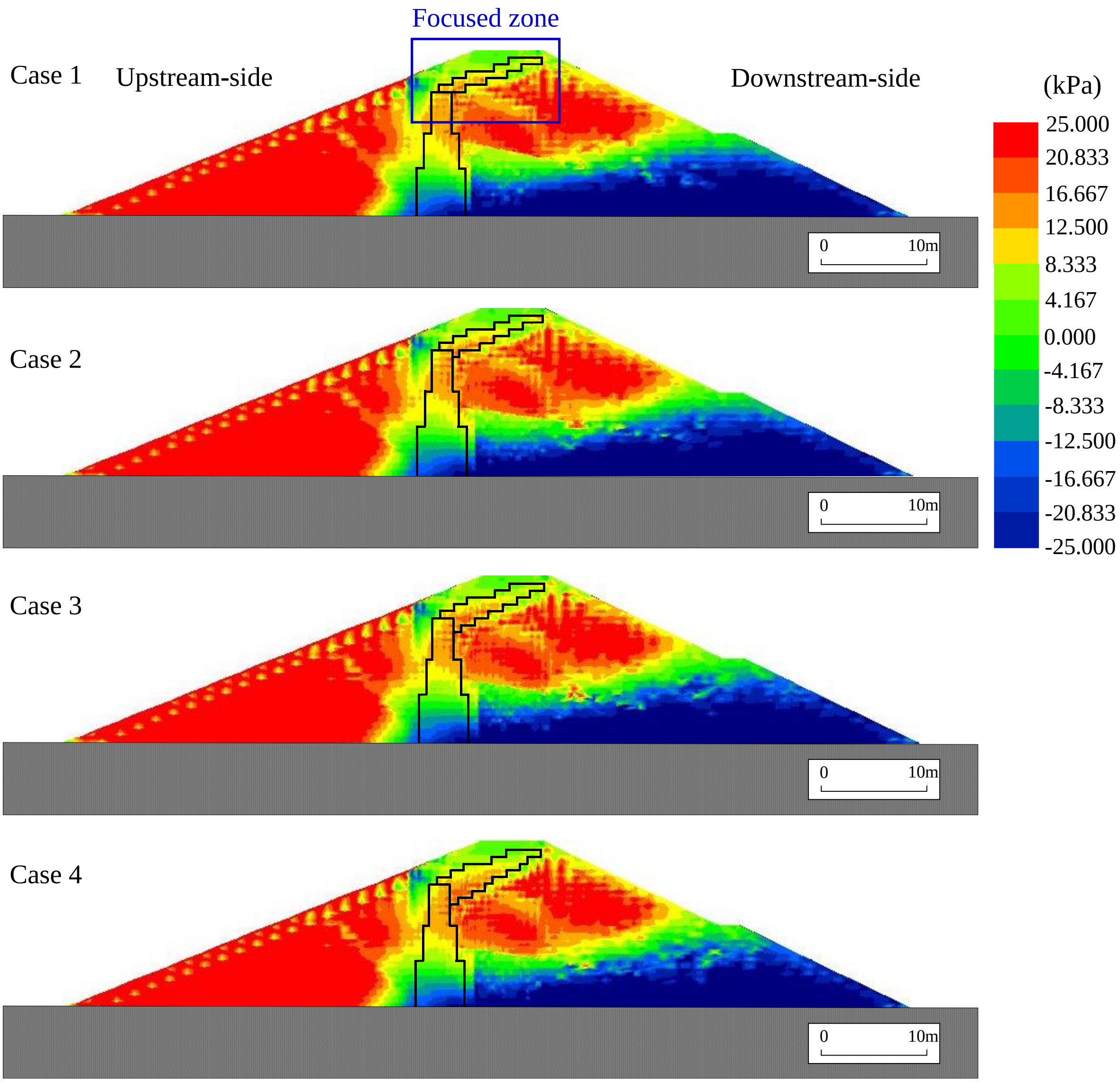


Figure 3.7 Result of the shear stress that occurred in the dam as a response to the direction of downstream-side (Case1-4)

As a result, the tendency of the shear stress that occurred in the dams showed the similar in each Case (Case1-4).Figure 3.8 and 3.9 shows the focused zone expanded in Figure 3.6 to identify the detailed change of shear stress. The following observations were made in the dam body (upstream and downstream dam body near core joint) and the core zone (existing core, core joint, heightened core) at times of dynamic response for upstream and downstream-side direction:

(a) Downstream-side dam body

At times of dynamic response for downstream-side, the share stress that occurred in the downstream-side dam was a larger. Here, the reason for the shear stress larger in the downstream-side dam body is expected that the dam body was compressed owing to the heightened core shape (tilted structural core) for downstream-side direction. As the core scale in each Case was expanded, it tended to increase slightly but it did not show a significant difference. Meanwhile, at times of dynamic response for upstream-side, the distribution of the shear stress showed the similar of the shear stress such as the direction of downstream-side, but the differences of shear stress in each Case were not clearly appeared.

(b) Upstream-side dam body

At times of dynamic response for downstream-side, the distribution of the shear stress acting on the upstream-side dam body tended to be relatively less than each zone analyzed in Figure 3.8, and there was no change of shear stress regardless of the expanded scale of the core in each case.

In addition, there was the same tendency as that of dynamic response for upstream-side with little change of shear stress. Thus, upstream-side dam body is expects to be no perceivable change for deformation during an earthquake.

(c) Existing core

At times of dynamic response for downstream-side, the shear stress on the existing core was larger while it acted less in dynamic response for upstream-side. The shear stress on the bottom part of the existing core became less for the upper parts, and it tended to increase slightly according to increase of the expanded scale of the core in each case.

In the upstream-side response, the distribution of the shear stress tended to be the same under downstream-side response, but the shear stress was less than in the dynamic response for downstream-side.

(d) Inclined core

At times of dynamic response for downstream-side, the shear stress on the upper part of the inclined core was low, but the concentration of the shear stress acted much near the joint of the inclined and existing cores. In respect to the influence of the expanded scale of the core in each case, the shear stress gradually moved to backside of the core (to downstream-side) as the expanded scale of the core is increased.

At times of dynamic response for upstream-side, the distribution of the shear stress put on the core joint tended to be the same as the one at times of dynamic response for downstream-side, but the shear stress was less than that of dynamic response for downstream-side.

(e) Core joint

At times of dynamic response for downstream-side, the shear stress that occurred in the core joint was bigger, and it tended to decrease according to increase of the expanded scale of the core in each case.

While in dynamic response for upstream-side, the distribution of the shear stress tended to be the same as the one in dynamic response for downstream-side, but the shear stress tended to decrease the value smaller than that in dynamic response for downstream-side.

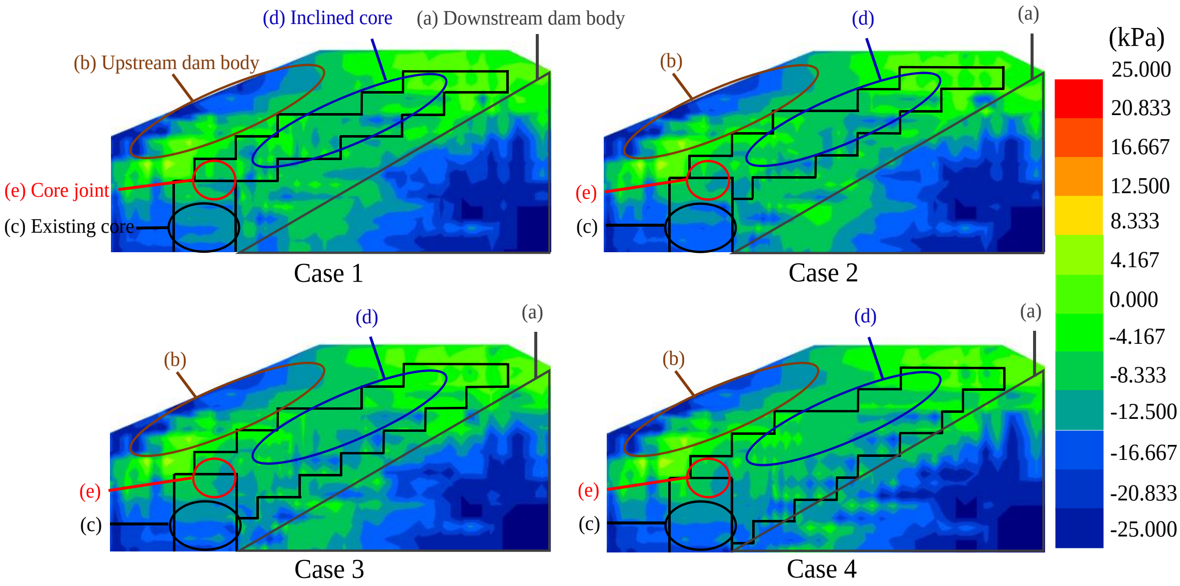


Figure 3.8 Result of the shear stress distribution in the response for upstream-side direction

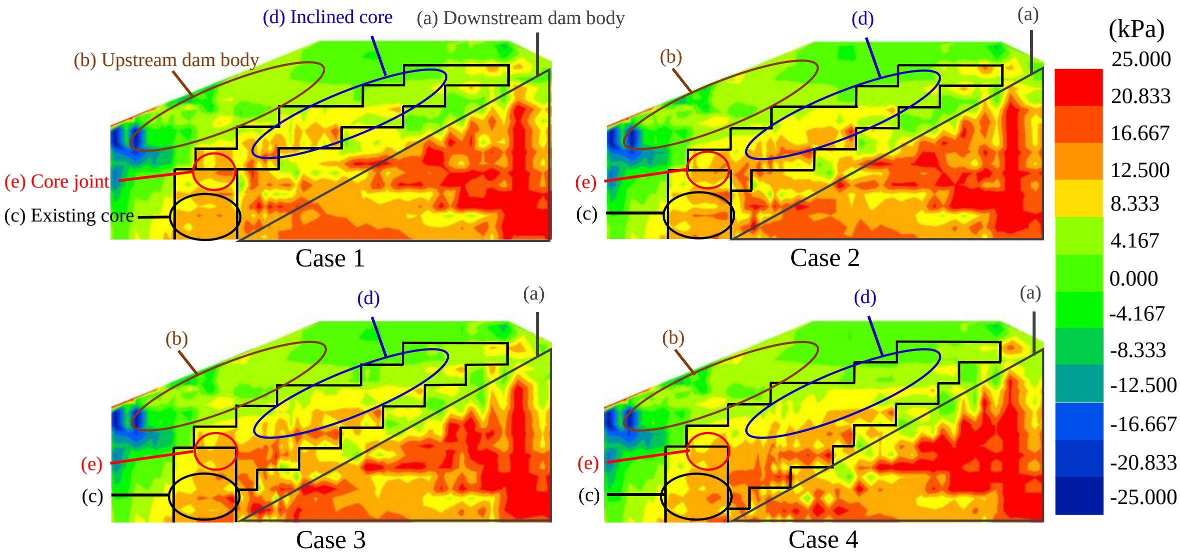


Figure 3.9 Result of the shear stress distribution in the response for downstream-side direction

3.2.4 Expanded effects of structural core on distribution of shear stress

Figure 3.10 shows the result of the maximum shear stress that occurred in the core joint focused in this study.

At times of response for upstream and downstream-side direction, it is thought that the difference in the shear stress put on the dam body or the core zone is caused by asymmetric structure (combined with an existing vertical core and an inclined core) of the heightened core. That is, the heightened core is susceptible to be deformed in downstream-side direction as the core is expanded in downstream-side direction. On the contrary, during the response for upstream-side direction, the heightened core was not likely to be deformed easily as the shear force is less than the one in the response for downstream-side direction. In connection to this, the influence of the shear stress put on the dam body according to increase of the expanded scale of core; the larger the scale of expanded structural core, the less the shear stress put on the overall core.

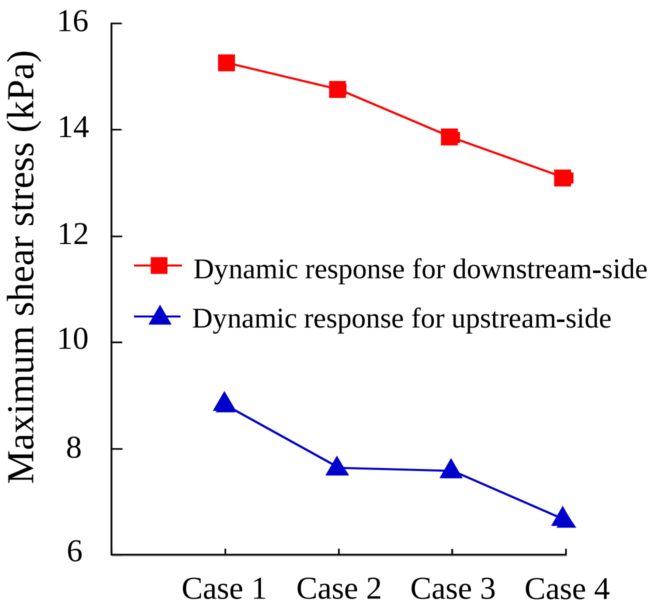


Figure 3.10 Comparison of the maximum shear stress that occurred in the core joint in each Case (Case1-4)

3.3 Dynamic Response Characteristics of Expanded Structural Core by Seismic Motion

In this section, the shear stress that occurred in the heightened dam by input seismic motions was assessed. Specifically, based on the dynamic response analysis by input sinusoidal wave, the core heightened dam by inclined-type was figure out a more vulnerable to the deformation at times of the response to downstream-side direction.

Therefore, the direction of dynamic response of the heightened dam was determined to the downstream-side direction for input seismic motion, the target analysis parts are considered in the same condition (focused zone) as shown in Figure 3.6 and 3.7 presented in section 3.2.3.

3.3.1 Seismic environment near Gyeryong Reservoir

The Korean Peninsula is hundreds of kilometers away from the Eurasian plate, as it is located in the southeastern interior of the plate[11)].

Figure 3.11 shows the earthquakes of magnitude ($4.0<M<5.0$) that occurred in Korea[12)] recorded from 1978 to 2012 years. Here, Gyeryong reservoir is placed in the middle area of Korea, it was located near between the earthquakes area recorded of magnitude 5.0 or higher.

Figure 3.12 shows details (site, scale, and focal depth)[12)] of the earthquakes of magnitude 3.0 or higher that occurred in the vicinity of the Gyeryong reservoir after 1978 (data of focal depth is opened since 1995). In regard to the seismic environment, it can be seen that most of the earthquakes that occurred in the vicinity of the Gyeryong reservoir are of a small scale and shallow focal depth. Based on the analysis results that identified these earthquakes as inland earthquakes, dynamic analysis was carried out.

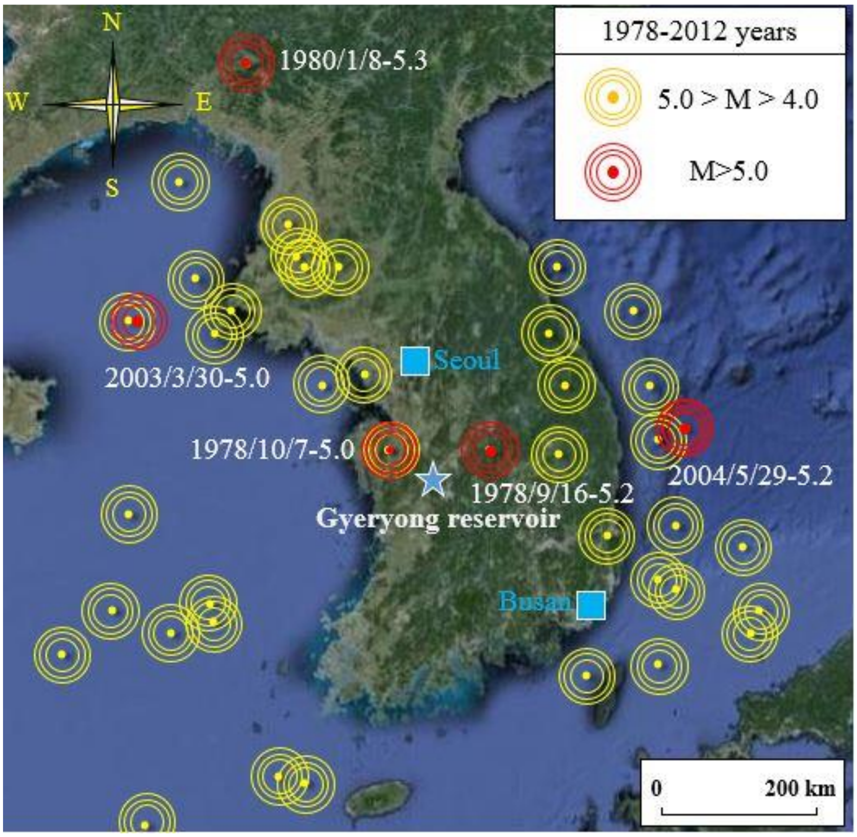


Figure 3.11 Earthquakes of magnitude (4.0<M<5.0) which occurred in Korea since 1978

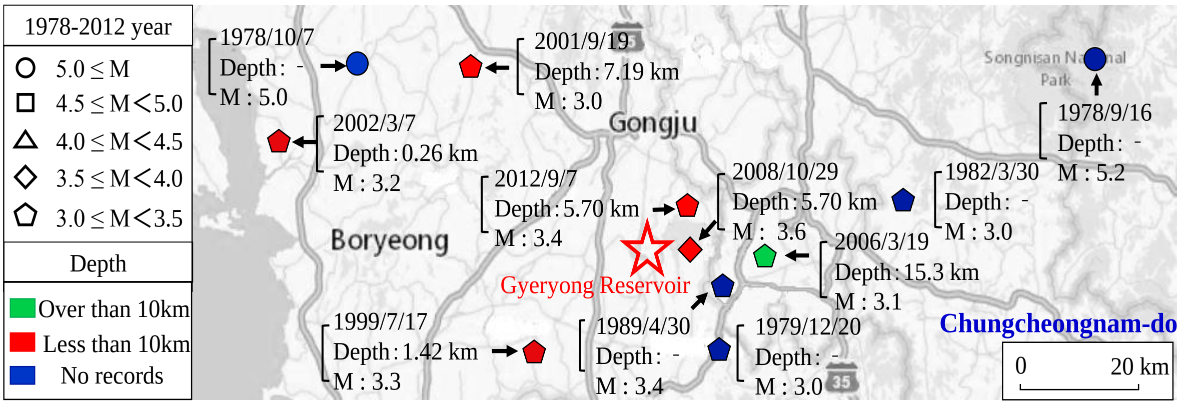


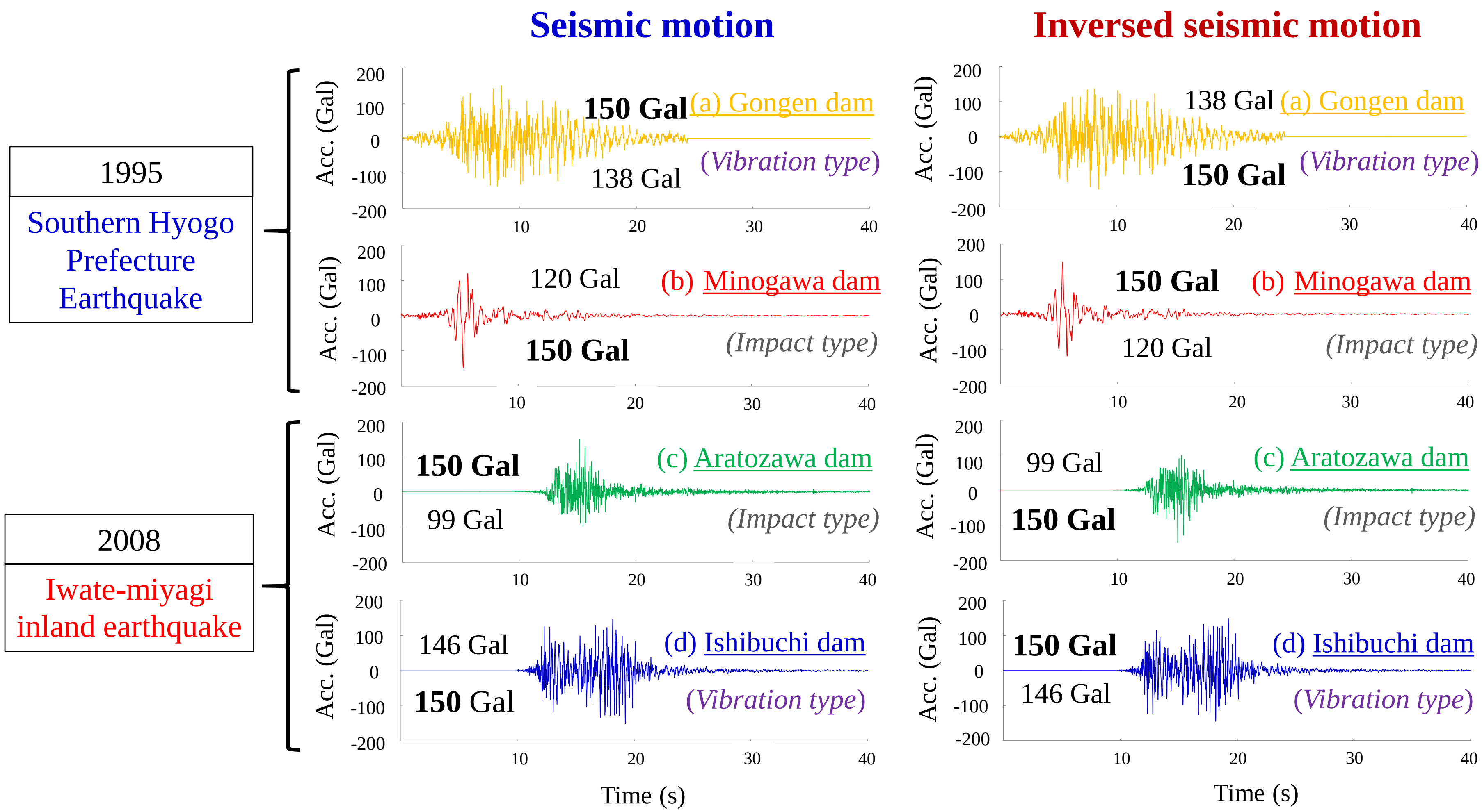
Figure 3.12 Number, scale and focal depth of the earthquakes of over 3.0 magnitude which occurred near Gyeryong reservoir since 1978

3.3.2 Input seismic motion

Considering the seismic environment near the Gyeryong reservoir, the four types of seismic motions were used as shown in Figure 3.13 measured in fill-type dams of Japan: the Gongen dam motion, associated with the 1995 earthquake in southern Hyogo Prefecture (2005)[13)]; the Minogawa dam motion, associated with the 1995 earthquake in southern Hyogo Prefecture (2005)[13)]; the Aratozawa dam motion, associated with the 2008 Iwate-miyagi inland earthquake (2013)[14)]; and the Ishibuchi dam motion, also associated with the 2008 Iwate-miyagi inland earthquake (2013)[14)]. In regard to this, Table 3.2 presents the height, ground motion measurement location, peak ground acceleration (PGA), and dam type for all four waveform types. The shear wave velocity and shear coefficient applied to the dynamic responses analysis were drawn from the physical properties of the Japanese ground base that can be considered to have a similar environment as that of the four dams analyzed despite the different dam field scale. In addition, in this study, each of the seismic motion and its inversed seismic motion were used to confirm the direction response of input of the seismic motion. Concretely, the reason that uses two type motions (seismic motion and it inversed seismic motion) is to compare the change of dynamic response for direction of tilted structure which is heightened core for inclined-type, and the maximum amplitude of all seismic motions has a different range as a pattern of – side (negative sign) or +side (positive sign) as shown in Figure 3.13. It also has been used by the national institute for land and infrastructure management (NILIM) of Japan, and this is one of the methods used to identify the differences of maximum amplitude of input seismic motion which has a different range as a pattern of – side or +side in each waveform. In connection to the maximum amplitude of input seismic motion and its inversed seismic motion, the same design seismic coefficient (150 Gal) used for dynamic response analysis by input sinusoidal waveform was applied.

Table 3.2 Dam field scale for four types of seismic motion

Field scale	Gongen dam	Minogawa dam	Aratozawa dam	Isibuchi dam
Type	Rock fill dam	Rock fill dam	Rock fill dam	Concrete face fill dam
Height (m)	32	47	74	53
PGA (Gal)	103	134	1023	1382
Location of seismometer	Foundation	Foundation	Foundation	Foundation



(a) Seismic motions

(b) Inversed seismic motions

Figure 3.13 Seismic motions measured in fill dams of Japan

3.3.3 Characteristics of natural frequencies of the seismic motions

In general, analysis of the sinusoidal waveform that has a constant cycle is simple but a seismic motion that converges with a many amplitude generated during the short period of time is somewhat complex. Thus, the Fourier transform is commonly performed to give understanding on characteristics of the output waveform. In regard to this, the seismic motions used for evaluation of the characteristics of natural frequencies utilized the actual seismic motions measured in four fill-type dams as shown in Figure 3.13, it can be classified into vibration type and impact type. Here, the reason to use two type waveforms is that there may be a differences of the dynamic performance between vibration type and impact type. Therefore, this study performed the basic natural frequency analysis to understand the effects on the core heightened dam induced by vibration type and impact type in each seismic motion. Figure 3.14 shows the comparison of the Fourier amplitude spectra of the four types of seismic motions, the results are as follows: the Gongen motion (Figure 3.14, a) nears the maximum amplitude of acceleration and lasts a relatively long time; its ground motion has a peak frequency of 1.6Hz. The Minogawa motion (Figure 3.14, b) is a short-duration intensive shock with the maximum amplitude of acceleration; its ground motion has significant frequency of 0.8-1.8Hz. The Aratozawa motion (Figure 3.14, c) has a large amplitude (16 s), but no significant frequency; its ground motion includes a wide frequency component over 0.4 Hz. The Ishibuchi dam motion (Figure 3.14, d): the amplitude range of acceleration is the similar tendency with Gongen motion, and its considerable ground motion exhibited relatively high frequencies of 2-3 Hz.

As a result, Gongen or Ishibuchi motions can be classified into vibration type and Minogawa or Aratozawa motions can be classified into impact type (See Figure 3.13).

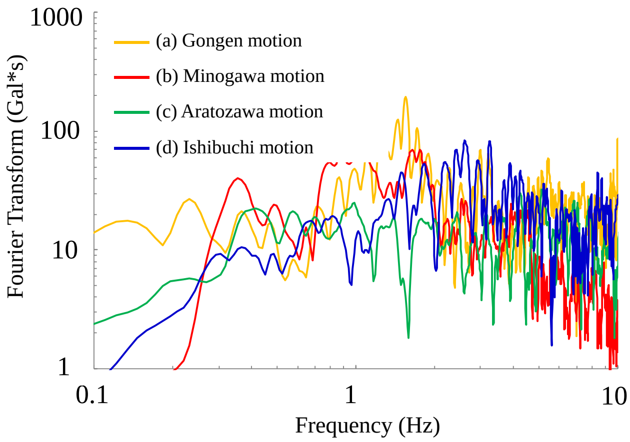


Figure 3.14 Results of the Fourier amplitude spectra for four types of seismic motion

3.3.4 Results of dynamic response analysis for seismic motions

Figure 3.15 and 16 (Gongen motion and its inversed motion), Figure 17 and18 (Minogawa motion and its inversed motion), Figure 19 and 20 (Aratozawa motion and its inversed motion), and Figure 21 and 22 (Ishibuchi motion and its inversed motion) illustrate the result of the shear stress that occurred in the dam at times of response for downstream-side.

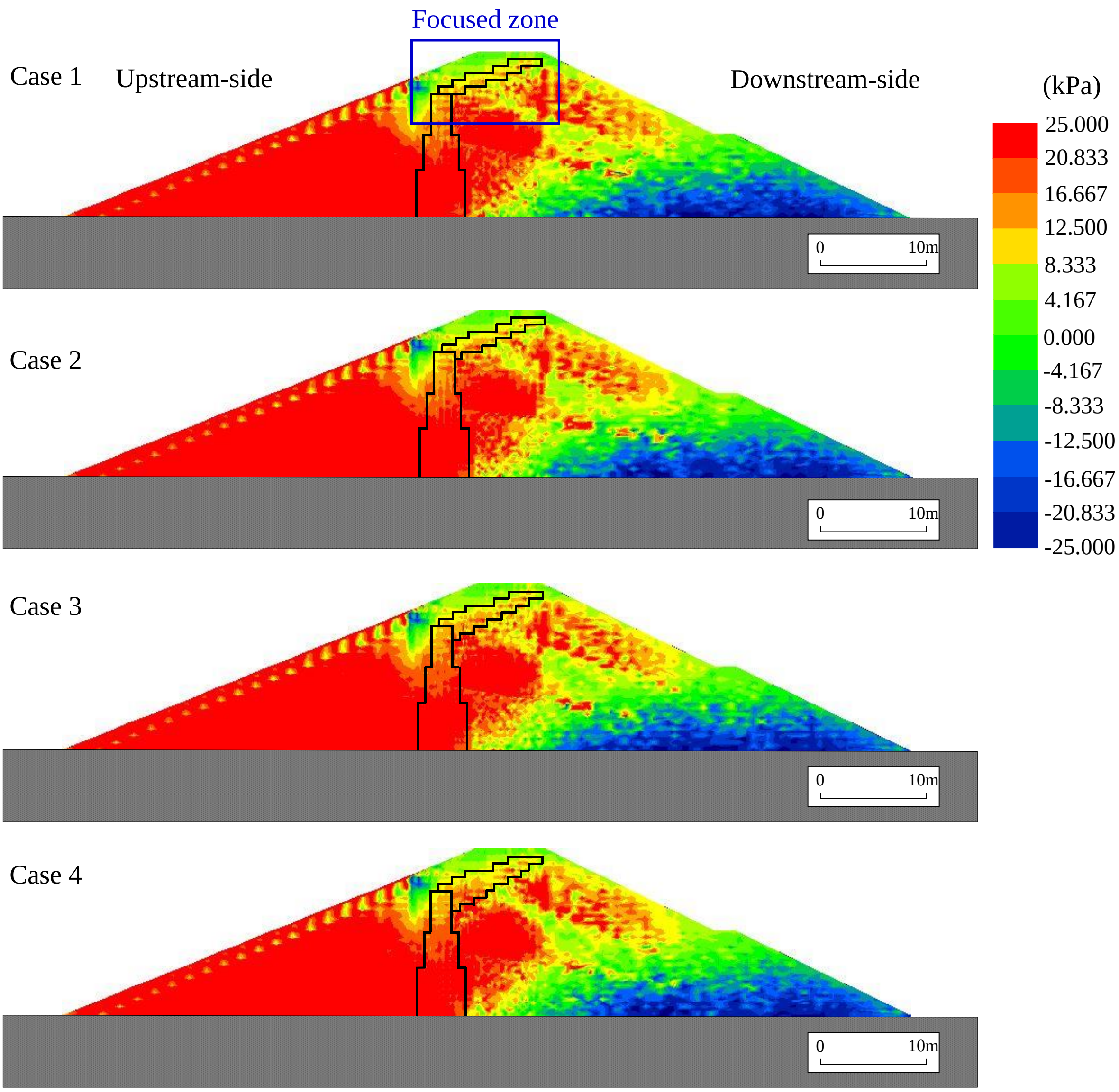


Figure 3.15 Result of the shear stress that occurred in the dam of Case1-4 (Gongen seismic motion)

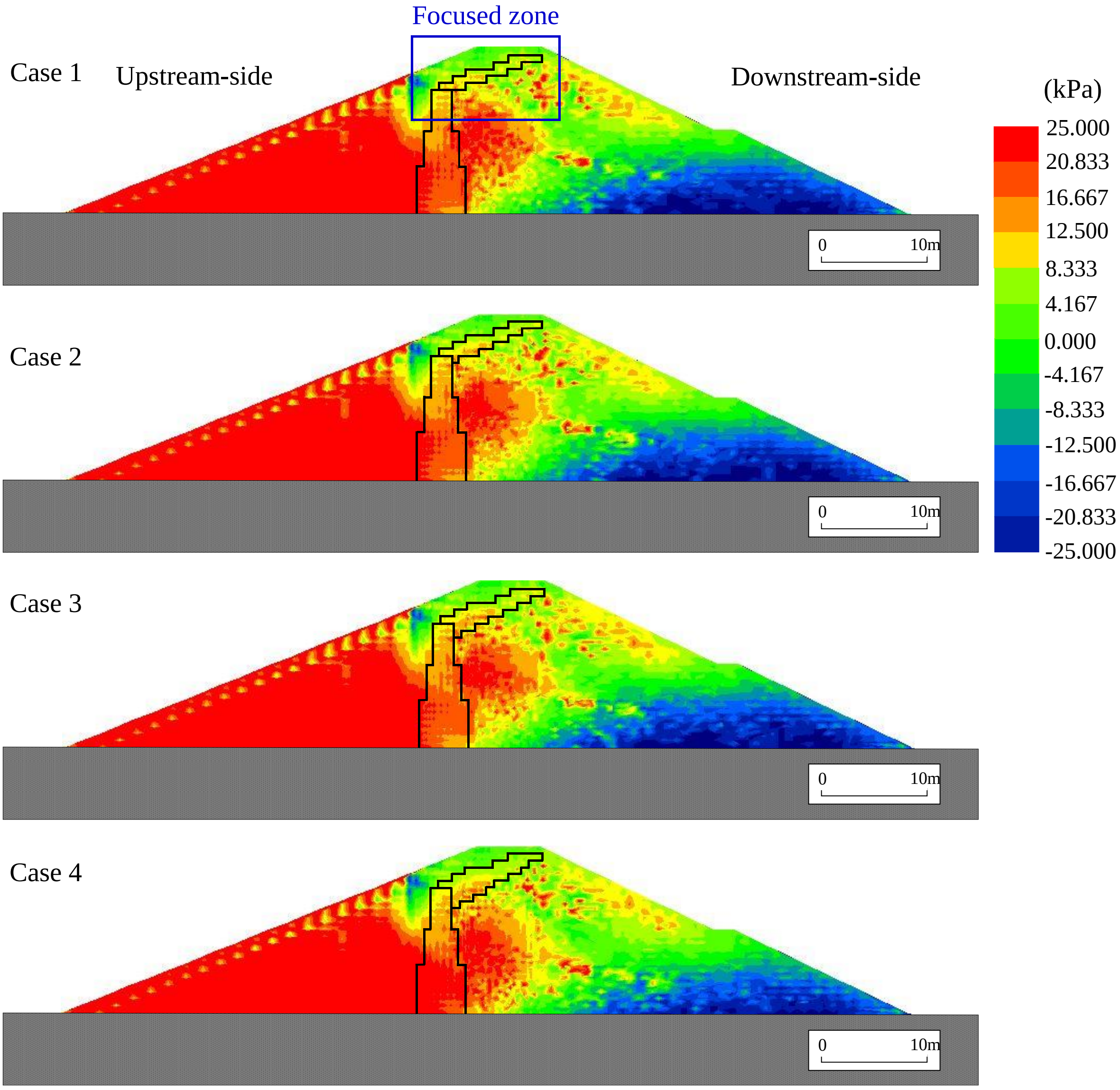


Figure 3.16 Result of the shear stress that occurred in the dam of Case1-4 (Gongen inversed seismic motion)

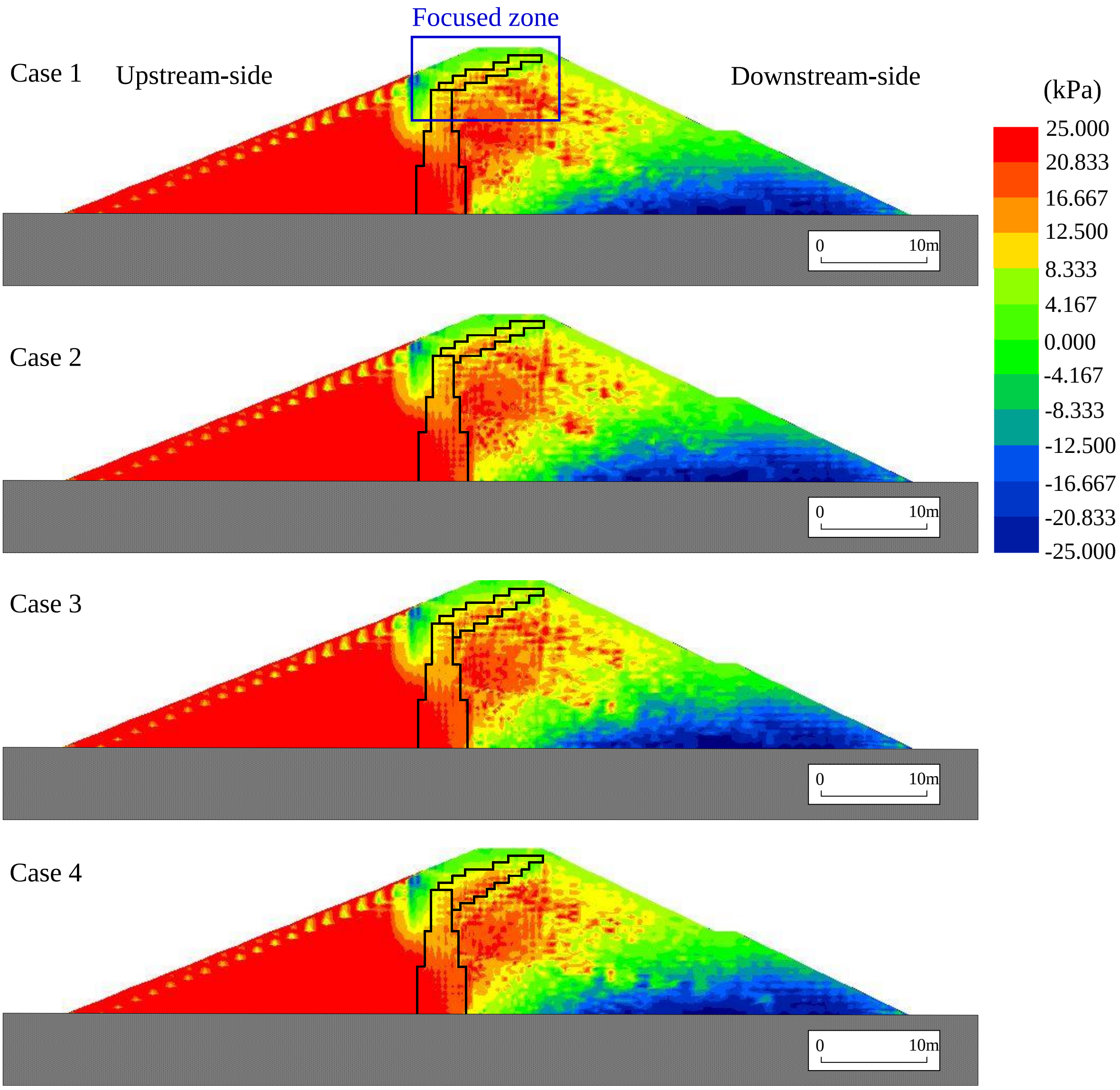


Figure 3.17 Result of the shear stress that occurred in the dam of Case1-4 (Minogawa seismic motion)

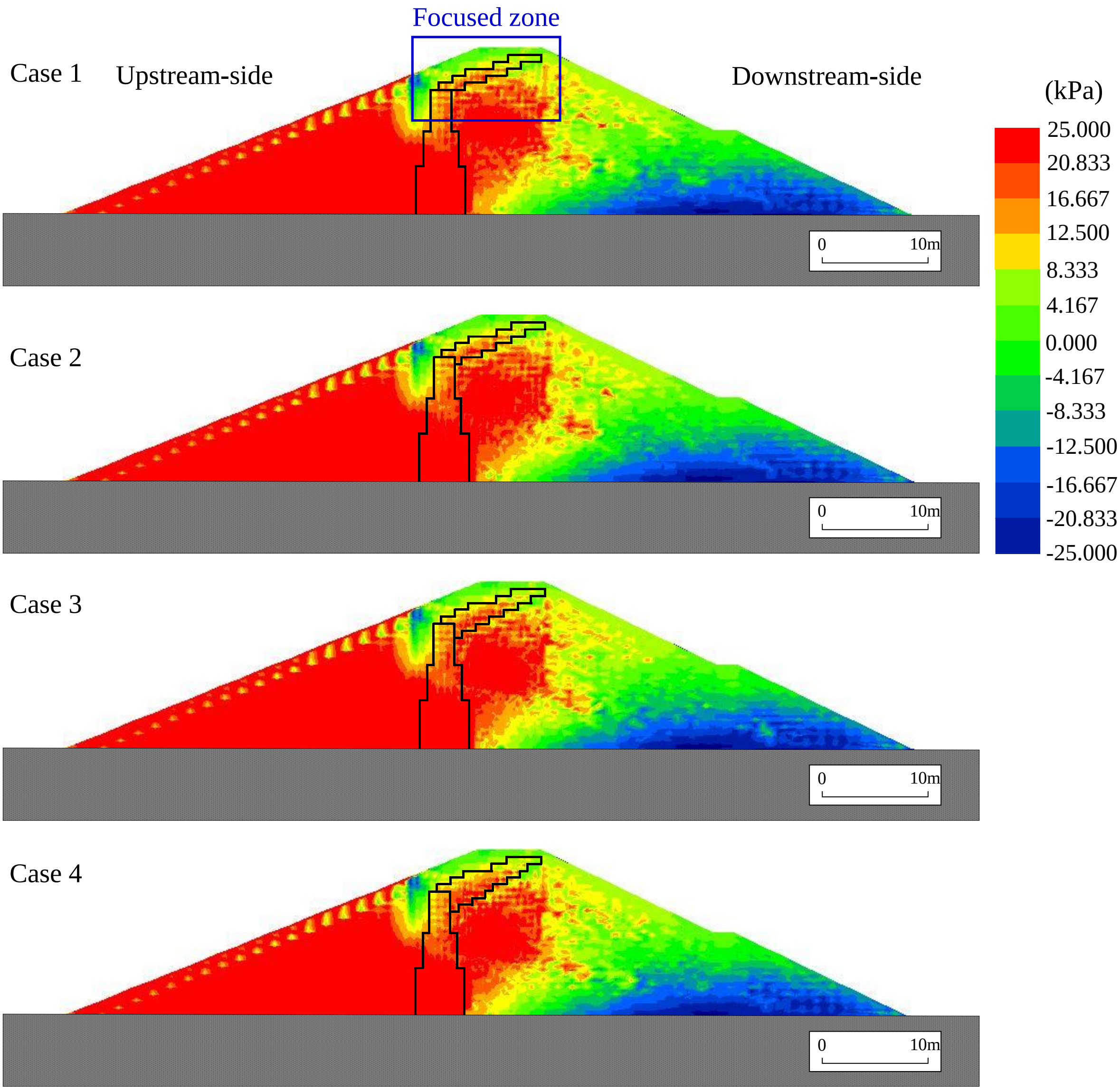


Figure 3.18 Result of the shear stress that occurred in the dam of Case1-4 (Minogawa inversed seismic motion)

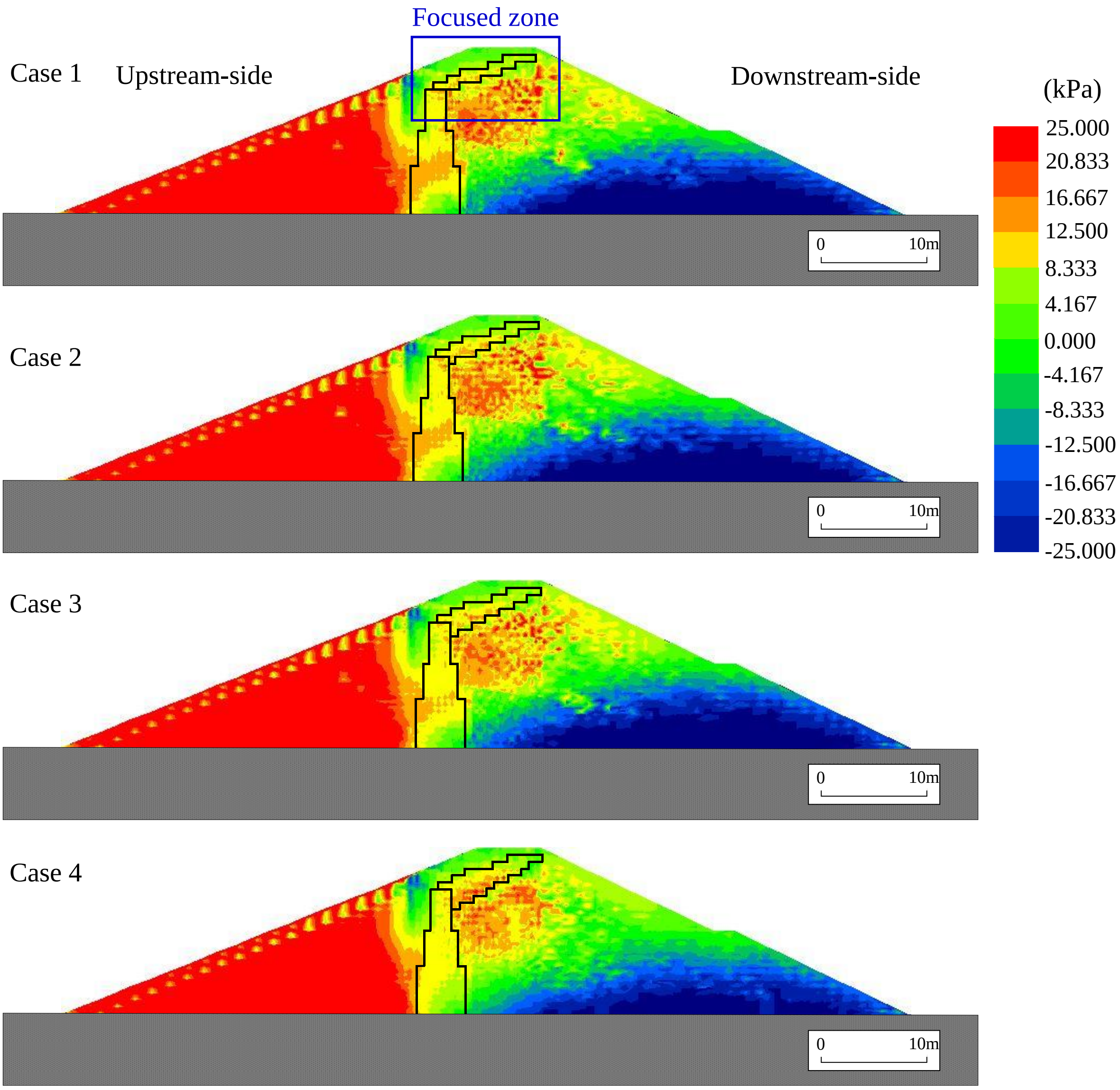


Figure 3.19 Result of the shear stress that occurred in the dam of Case1-4 (Aratozawa seismic motion)

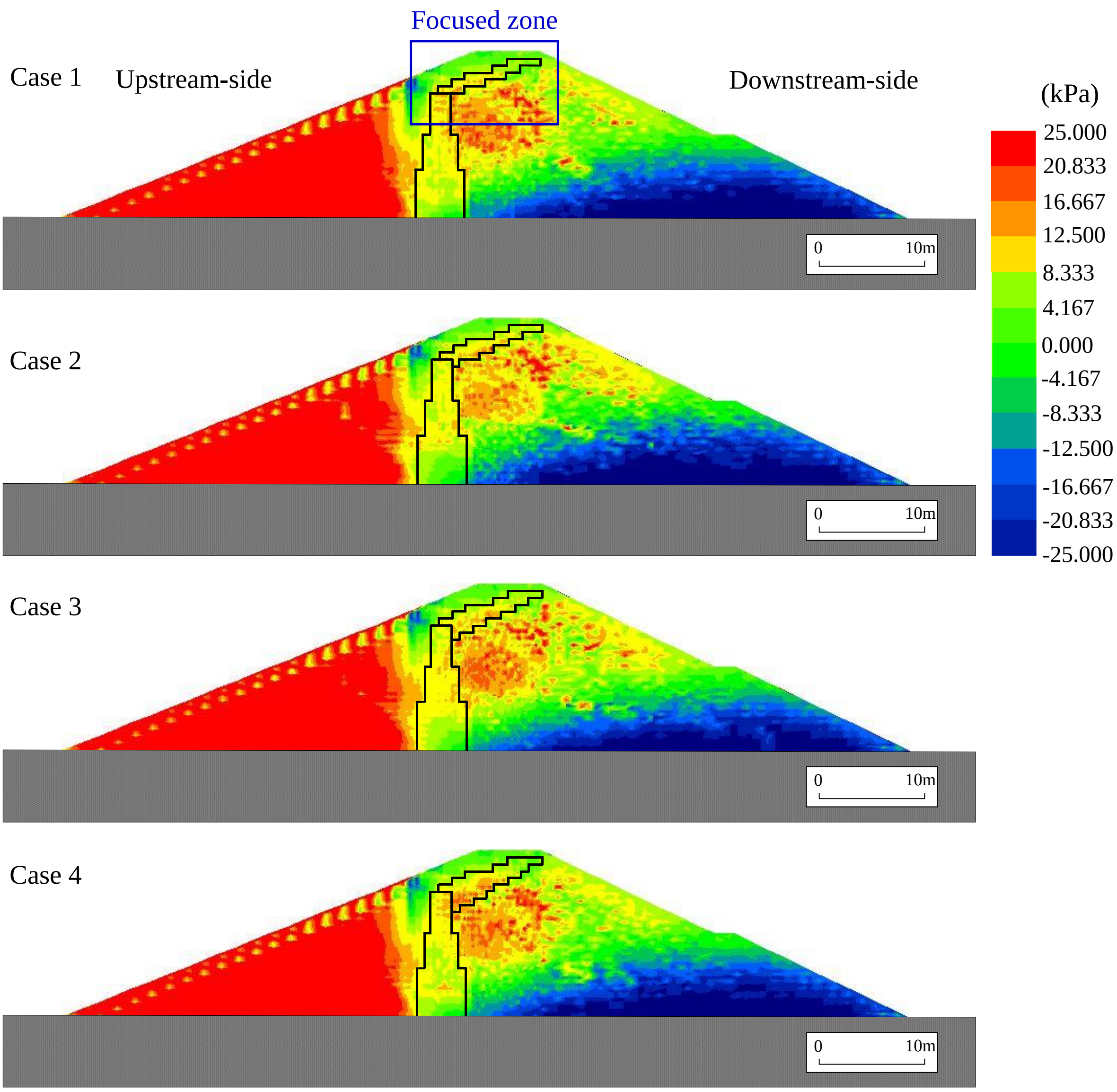


Figure 3.20 Result of the shear stress that occurred in the dam of Case1-4 (Aratozawa inversed seismic motion)

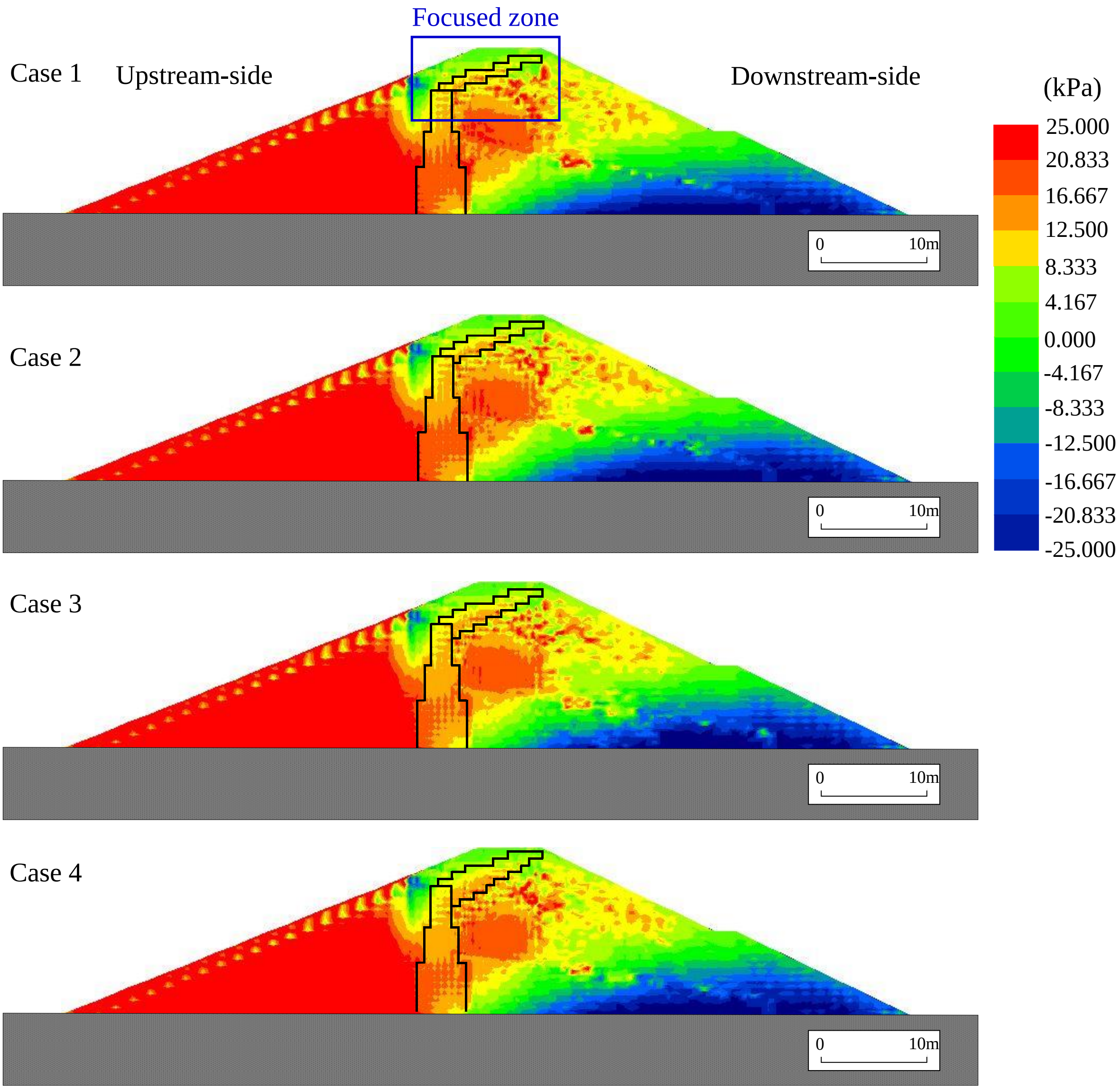


Figure 3.21 Result of the shear stress that occurred in the dam of Case1-4 (Ishibuchi seismic motion)

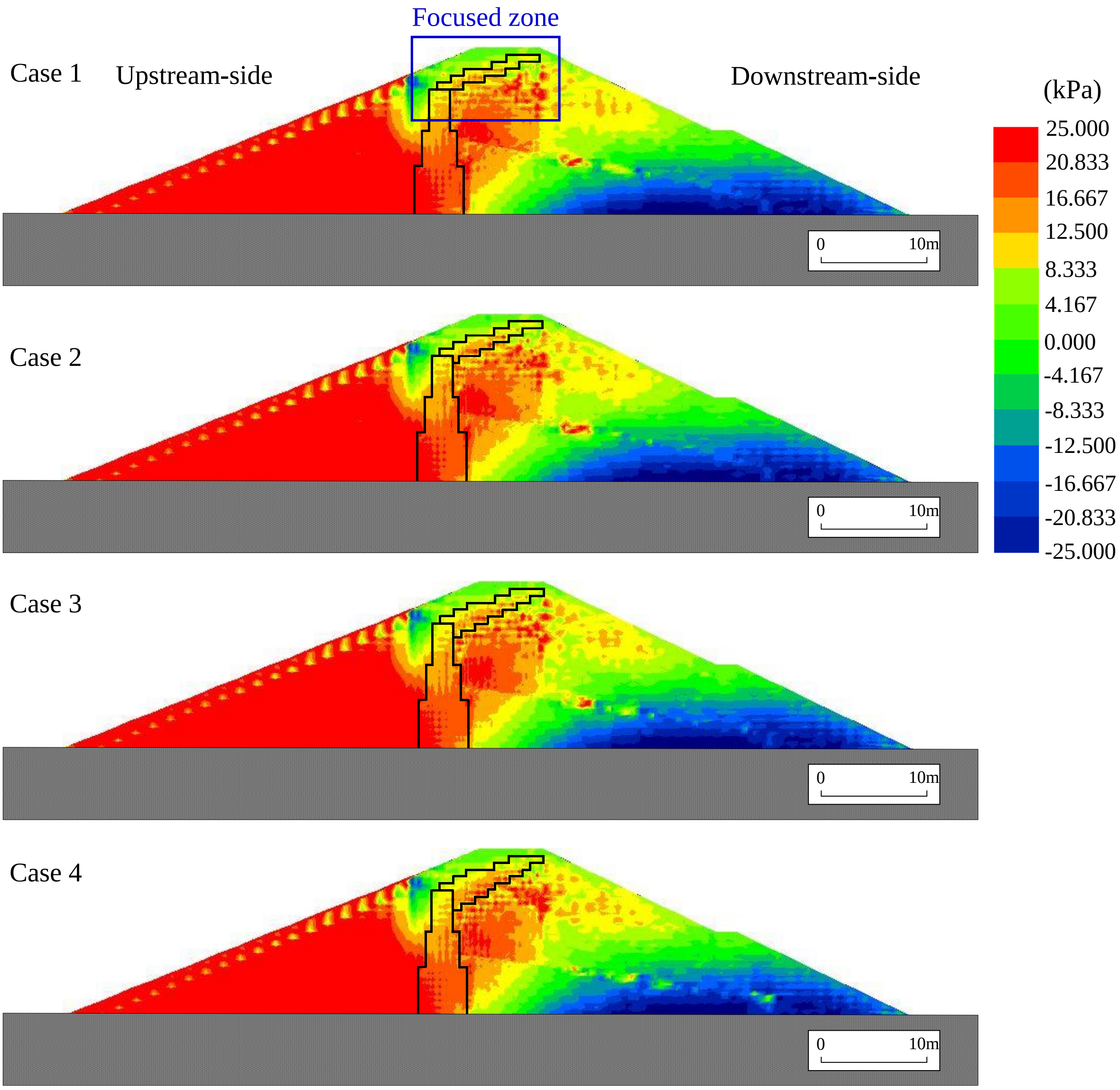


Figure 3.22 Result of the shear stress that occurred in the dam of Case1-4 (Ishibuchi inversed seismic motion)

The distribution of shear stress that occurred in the focused zone as presented in Figure 3.15-22 were discussed, and Figure 3.23-30 shows the result of the shear stress that occurred in focused zone. The following observations were made in the dam bodies (Upstream and downstream dam-side near core joint) and the cores (Existing core, core joint, inclined core) at times of downstream response:

(a) Downstream-side dam body

A large shear stress occurred in the downstream-side dam body in response to the downstream direction. No remarkable changes were observed in all the four cases although the shear stress range slightly increased in accordance with their scales. The reason for the shear stress increase in the downstream-side dam body is assumed to be the pressure exerted on the downstream by the structure of the expanded core that is tilted towards the downstream side, which increases the shear stress on that side.

(b) Upstream-side dam body

The overall shear stress distribution was low in the upstream-side dam body when responding to the downstream direction. The influence of the expanded scale of the core turned out to be almost non-existent.

(c) Existing core

When responding to the downstream direction, the downstream-side core showed a smaller shear stress than the upstream-side core. In addition, no change in shear stress at the existing core was induced by the core scale expansion.

(d) Inclined core

When responding to the downstream direction, a slight shear stress occurred in the upper part of the expanded core, but it appeared almost smaller value than the shear stress that occurred in the other part. In respect to the influence of the scale of the inclined core (each case), the effect of the shear stress expanded to small areas as the scale of the core increased.

(e) Core joint

When responding to the downstream direction, the overall shear stress concentrated on the joint. Further, in proportion to the expanded scale of the core joint, the shear stress exerted on the core joints shifted toward the downstream side.

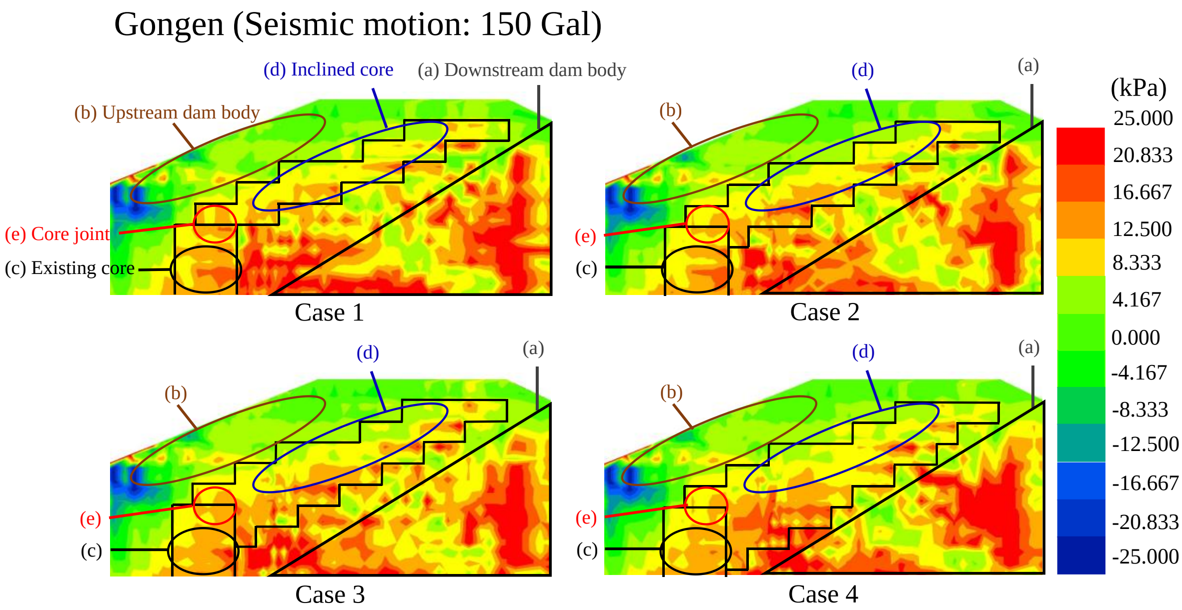


Figure 3.23 Shear stress distribution near the core joint (Gongen seismic motion)

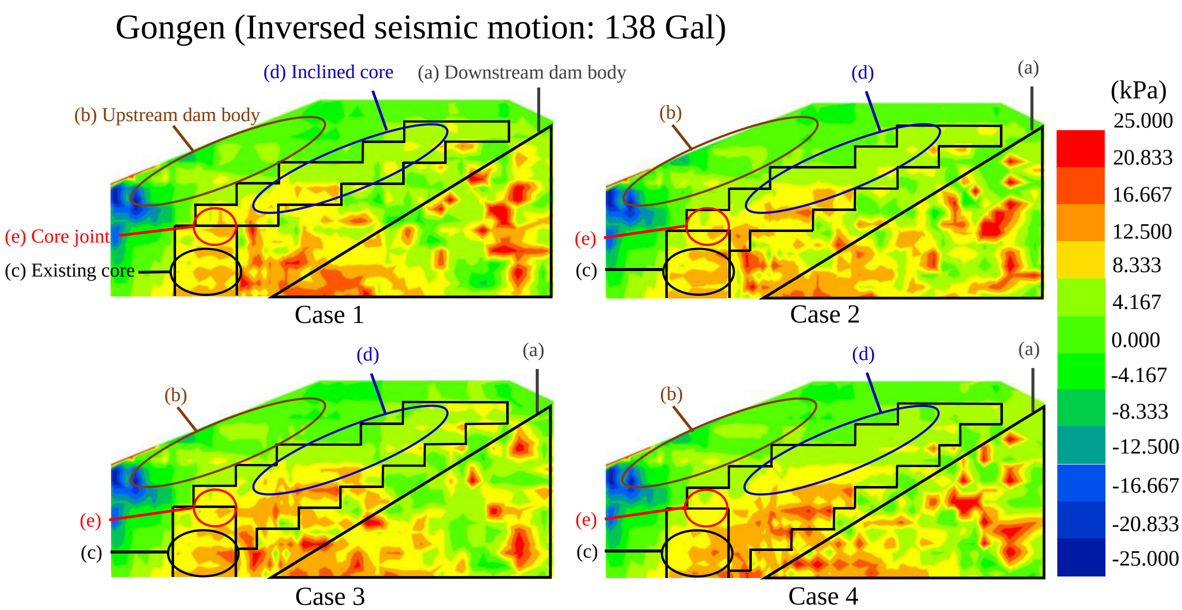


Figure 3.24 Shear stress distribution near the core joint (Gongen inversed seismic motion)

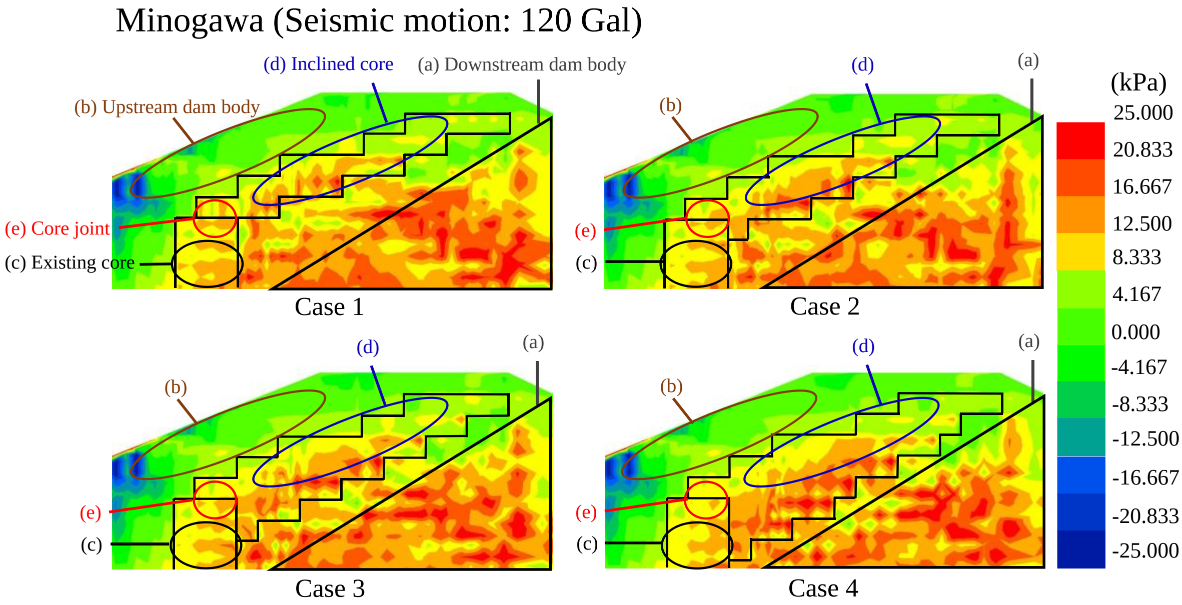


Figure 3.25 Shear stress distribution near the core joint (Minogawa seismic motion)

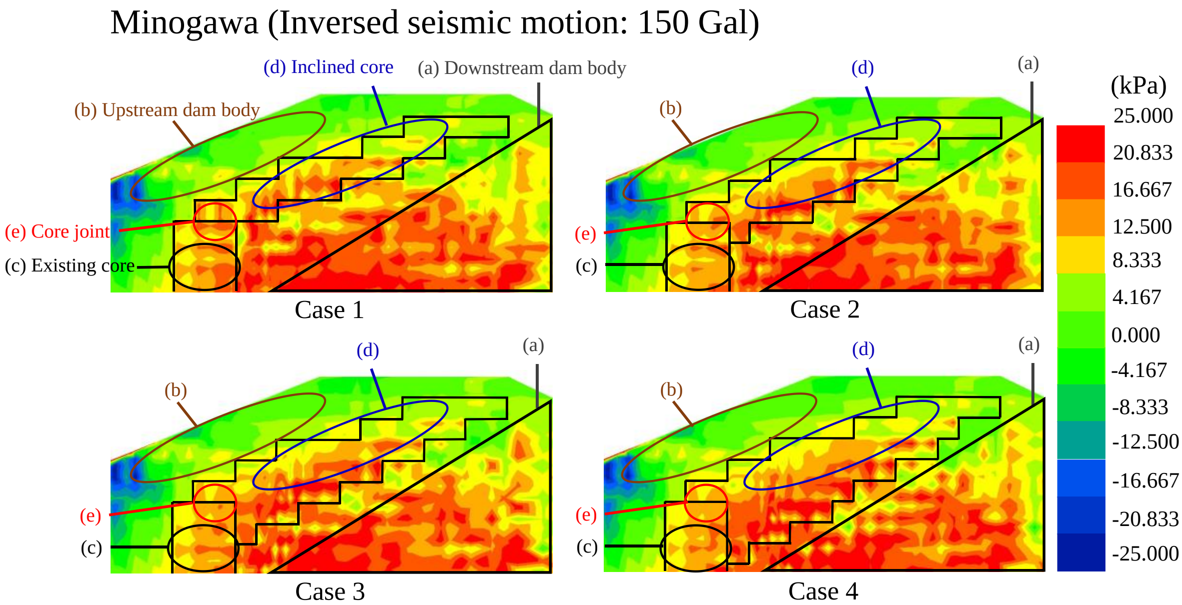


Figure 3.26 Shear stress distribution near the core joint (Minogawa inversed seismic motion)

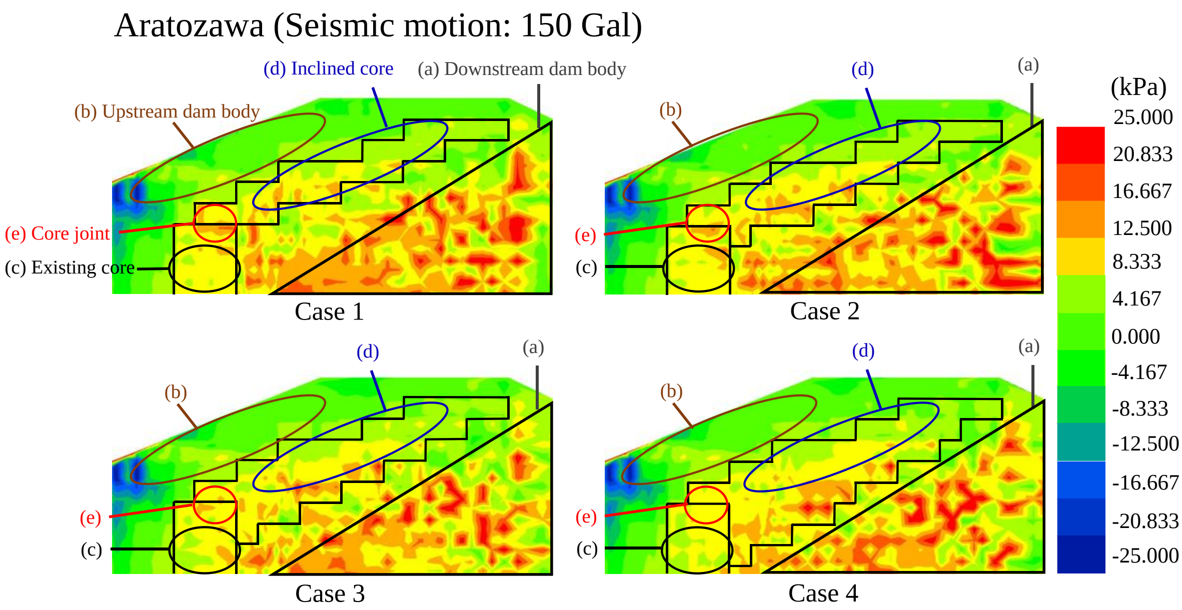


Figure 3.27 Shear stress distribution near the core joint (Aratozawa seismic motion)

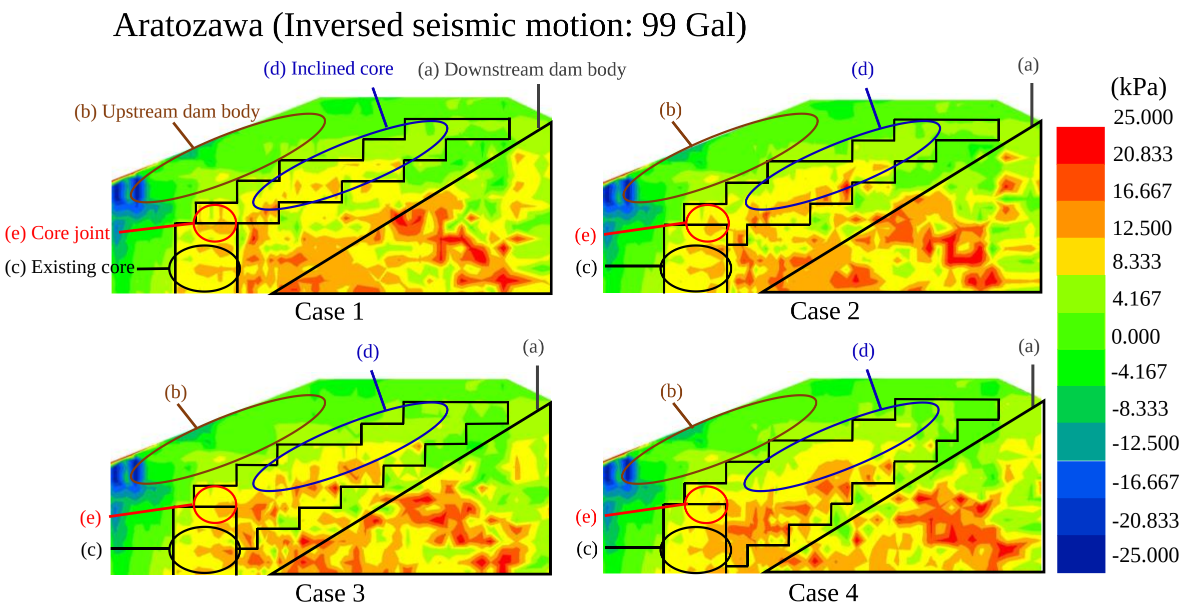


Figure 3.28 Shear stress distribution near the core joint (Aratozawa inversed seismic motion)

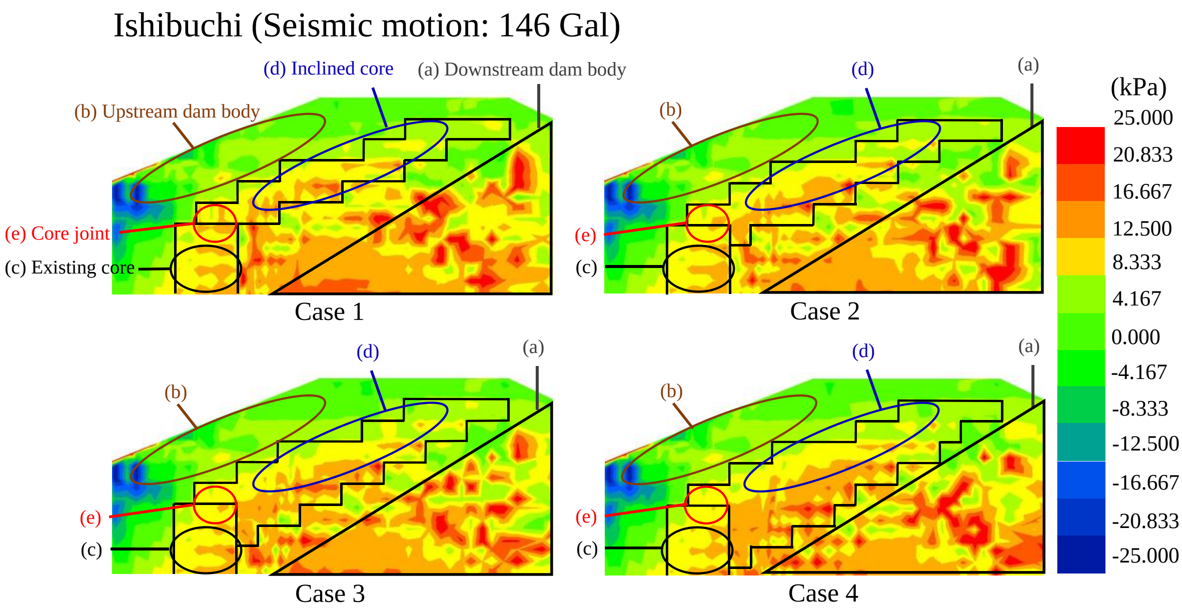


Figure 3.29 Shear stress distribution near the core joint (Ishibuchi seismic motion)

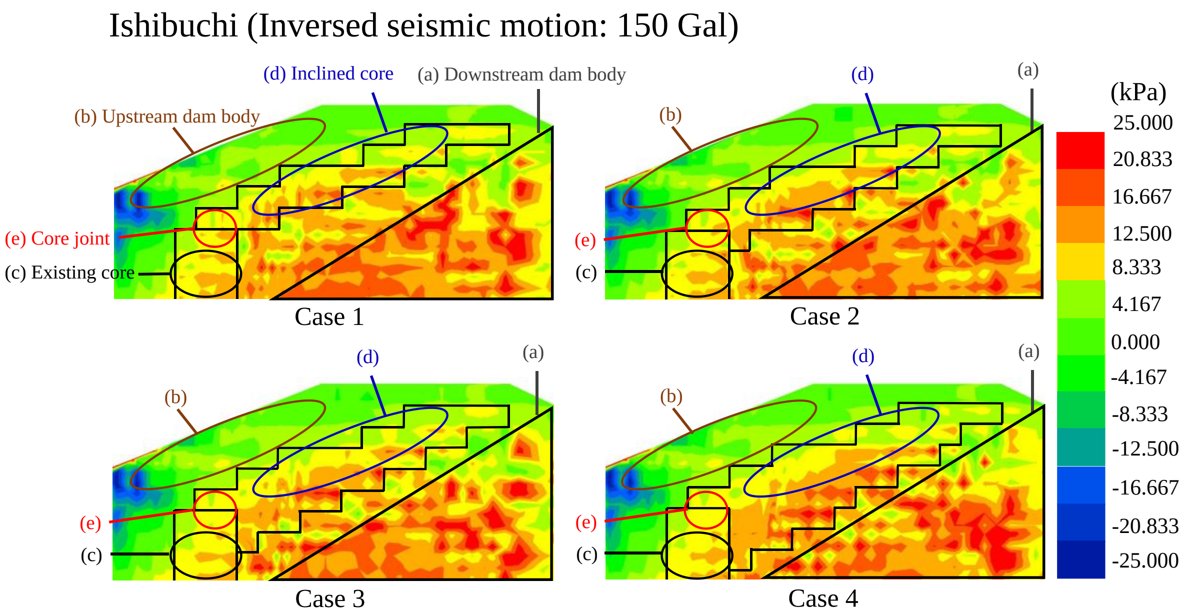


Figure 3.30 Shear stress distribution near the core joint (Ishibuchi inversed seismic motion)

3.3.5 Expanding effects of the core on distribution of shear stress

Overall tendency of shear stress acting on the dam bodies and cores are almost similar with the result obtained in the dynamic response analysis by input sinusoidal waveform. The result obtained in the shear stress by input seismic motions, it was verified that the shear stress generated in the core joints, which is the main focus of this study, tended to decrease in proportion to the expanded scale of the core. Table 3.3 outlines the maximum shear stress value and the time taken to reach the maximum level.

Figure 3.31 shows the relationship between the expanded scale of the core and the shear stress acting on the core joint for each seismic motions and its inversed seismic motions. As a result, it reveals a tendency of a linear decrease in shear stress at the core joint in proportion to the expanded scale of the core in response to the Minogawa and Ishibuchi dam seismic motions. However, against the Gongen dam motion,, the shear stress decreased in Case 1-2, show much decrease in Case 2-3, and showed a large decrease in Case 3-4. Against the Aratozawa dam motion, Case 1-3 showed a slight decrease in shear stress, but Case 3-4 showed a considerable decrease. Though there are some irregular tendencies in the degree of decrease in each Case obtained in the dynamic response analysis by input seismic motions, the overall results of the shear stress acting on the core joint are decreased gradually in all seismic motions according to the expanded scale of the core.

Table 3.3 Maximum shear stress value at the core joint

Case No.	Maximum shear stress (kPa) at the joint core 【s】							
	Gongen waveform		Minogawa waveform		Aratozawa waveform		Isibuchi waveform	
	Seismic	Reverse	Seismic	Reverse	Seismic	Reverse	Seismic	Reverse
Case 1	14.48 【9.23】	13.39 【8.76】	13.17 【5.79】	16.73 【5.41】	14.04 【15.29】	13.39 【14.63】	12.76 【13.35】	11.81 【13.48】
Case 2	12.89 【9.23】	11.78 【8.76】	12.46 【5.79】	14.51 【5.41】	14.03 【15.29】	11.57 【14.63】	11.74 【13.35】	10.83 【13.48】
Case 3	12.84 【9.23】	11.48 【8.76】	11.83 【5.79】	13.80 【5.41】	13.58 【15.29】	10.71 【14.63】	10.98 【13.35】	10.06 【13.48】
Case 4	11.82 【9.23】	10.16 【8.76】	11.20 【5.79】	13.59 【5.41】	9.08 【15.29】	10.48 【14.63】	10.50 【13.35】	9.90 【13.48】

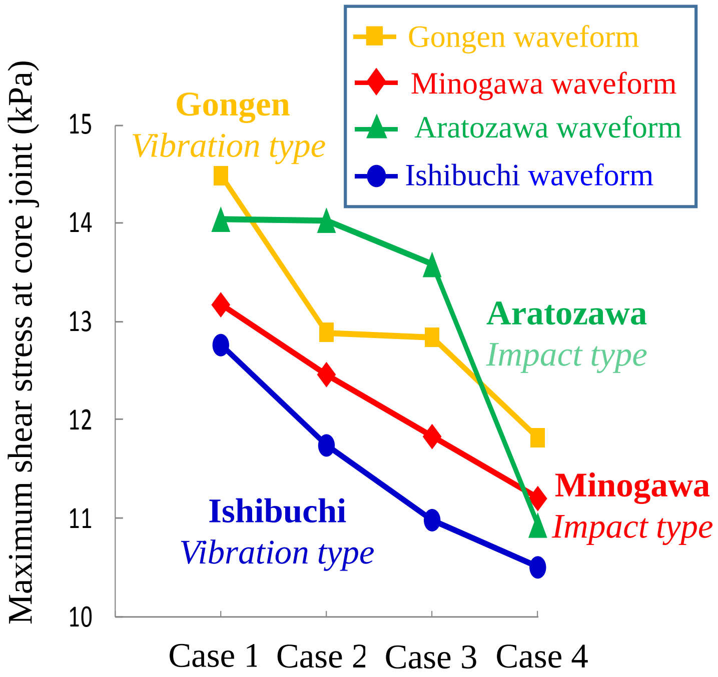


Figure 3.31 Maximum shear stress that occurred in the core joint

3.4 Summary

In this chapter, study was performed to investigate the expanded effects of core joint on the dynamic performance of a core heightened dam by inclined-type. Dynamic analyses were carried out to four different structural cores and four different seismic motions. The following are the summary.

(1) For the evaluation of natural period according to the expanded scale of the core, no perceivable changes were observed in the natural period of the dam body after the core expansion, which indicates that the dam body will not be affected expanded structural core construction method.

(2) In sinusoidal waveforms, the shear stress acting on the core joint is more affected by downstream direction response than upstream direction response. This implies that the downstream direction tends to be deformed easily.

(3) In all seismic motions, the shear stress acting on the downstream-side dam body was greater. This may be ascribed to the structural cores being tilted toward the downstream side where the downstream-side earth-fill zone is compressed. Further, the shear stress acting on the core joint was found to decrease a tendency according to the scale increases of the core expansion.

(4) In all seismic motions, while the shear stress acting on the core joint zone generally decreased, there was a considerable discrepancy in the degree of decrease. This implies that an optimal configuration between the structural cores and scale can be obtained.

From the above results, it is confirmed that the dynamic seismic response (shear stress) can be controlled as means of reducing the core deformation and cracks. On the other hand, the construction cost can be increased as the expanded scale of the core increased. Therefore, further research is necessary to establish optimal scale of the core joint structures in terms of work efficiency and rational construction cost.

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Chapter 4

4. Economical Optimum Design of Inclined-type Structural Core

4.1 Introduction

In this chapter, economic optimum design of the inclined-type structural core for heightening reservoir dam was outlined. On the basis of the results obtained in chapter 3 and 4 (seepage characteristics and dynamic performance for the expanded structural core), there is an increase in the construction cost in each scale of the structural core; accordingly, the optimal scale of the expanded structural core must be determined based on the assessment whether the expanded core is an economic as means to guarantee the rational construction cost. Therefore, the evaluation method of the optimum scale of the expanded structural core with economic validity was proposed and introduced, for the background knowledge of this study as example in South Korea outlined below.

A large proportion of the infrastructures for public facilities (electricity, water supply, etc.) is owned by the government, South Korea manages and operates its water resources through public enterprises. Especially such as related to the water charges for irrigation, it was supported as a full exemption to farmers since 2000 due to farmers' long-standing demands. However, this policy appears to be taking a short-term path of least resistance in order to maintain a policy of self- sufficiency in staple grains, but it is clearly unsustainable in the medium- to long-term (OECD: Agricultural Water Pricing, 2010)[1). In regard to this, the perspectives by report of agricultural water pricing, the alternatives or improvement schemes are needed in South Korea. Meanwhile, South Korea's annual economic growth rate (Present time: 2.5–3.5%), as estimated by the National assembly budget Office from 2013 (NABO, 2013)[2), is relatively high compared with those of OECD countries in the last ten years, and because of the rapid privatization of public enterprises, water usage cost can fluctuate rapidly. Moreover, with drought periods[3) expected to last about 3.4 times longer than in the past (1977-2006 years) due to recent rapid climate changes, water shortages caused by the securing of water value, such as household, agricultural, and industrial use water, are expected to result in early fluctuations in water prices (MLTM, 2011). In regard to this, this study focused on the value of water changed by elapsed time, and it was compared with the construction cost-induced by expanded structural core construction method.

4.2 Index of Life Cycle Cost for Economical Optimum Design of Inclined-type Structural Core

In general, a LCC (Life Cycle Cost)[4] analysis as one of cost evaluation method is commonly used to perform the economic feasibility and/or validity on the objectives one, its LCC analysis is defined as the total cost throughout its life cycle costs including rebuilding, design, repair and/or reinforcement, maintenance, etc. LCC can be expressed as following Eq. 4.1, concerning the objectives of this study.

LCC = Initial Construction Cost + Running Cost + Rebuilding Cost · · · · · · · · · · ·Eq.4.1

Here, LCC: Life Cycle Cost

Initial Construction Cost: Total construction cost for heightening dam

Running Cost: A maintenance and repair etc. all costs during life time of the heightened dam

Rebuilding Cost: A cost to construct, at current prices, and exact duplicate or replica of the structure, using like kind and quality materials, construction standard, design, layout and quality of workmanship.

In Eq.4.1, LCC has a lot of factors influenced to the cost estimation like Initial Construction Cost (ICC) and Running Cost (RC), etc. With regard to the factors of LCC, this study only applied to the sum for the ICC (Initial Construction Cost: work efficiency costs regarding the material and construction costs) and RC (Running cost: total maintenance and repair etc., cost during life time of the heightened dam) except for the rebuilding and other user costs. Because this study is subjected to discrete portion (core joint zone: expanded structural core) in the dam heightening work of the existing reservoir, and thus the estimation of LCC can be complicated due to the environment differences in each reservoir when the rebuilding and other user costs included.

In particular, there need to be rearranged in the estimation of RC which is define as a management cost, repair cost and reconstruction cost during life cycle of dam since the subjected dam-type was the zoned earth fill-type which is vulnerable to the infiltration in rainfall patterns and/or water level change of the reservoirs. In case of the zoned earth fill-type dam, the cause of the dam accident and failure patterns (overtopping, piping, and erosion, settlement of the foundation, differential settlement occurred by the material compressibility, etc) are very various, and it is difficult to make the cost estimation. Regarding RC (Running Cost) in the zoned earth fill-type dam, here the estimation approach and the reasons was discussed as follows.

The concept of RC (Running Cost) is generally included to benefits (ex: added dam water storage, increase of a river-management flow and irrigation use, etc.) that can be obtained from heightening work with regard to the cost estimation as means of decreasing the disaster damage by flood and droughts, etc. Here, dam (earth fill-type) accident and failure patterns including the disaster periods are mainly induced by the external environment of the reservoirs like rainfall patterns, ground water level, geographical features and soils characteristics, and thus it is hard to generalize about the consideration of all factors in a general reservoir dams. Thus, this study focused on the leakage water that has long been a major problem for the maintenance of the dam safety, it is still occurring in the earth fill-type dam due to its material characteristics which was made of soils (silt, sand, clay etc.). Here, understanding the leakage water which is influencing to the dam safety is the most important variable, and this can be one of biggest problem like a water shortage relation to the future climate change. In regard to this, since each reservoir has different environment, it is hard to consider the all factors related to the benefits induced by the heightening work as mentioned above. Thus, this study focused on the leakage water that can be applied to the zoned earth fill-type dam.
On the other hand, the leakage water from the dam body can be estimated to be minus benefits (negative benefit) which aren't generally considered as the benefits, since the leakage water is the most influence to the dam safety. In that context, this study suggests that the leakage water should be estimated as the leakage loss cost which can be identified as one kind of the running costs during the life cycle of the dam as the following Eq.4.2.

Loss or price of water leakage = Loss of benefit = One kind of running cost · · · · Eq.4.2

In summary, the benefit was considered to the water leakage which is the biggest factor influencing to the dam safety in relation to the one kind of loss of benefit. In regard to this, leakage loss cost which can be generalized in zoned fill-type dam was subjected, and it was defined into OLC (Objective Loss Cost: leakage loss cost) in this study. For the estimation of ICC (Initial Construction Cost), it was defined into OICC (Objective Initial Construction Cost), and OLCC (Objective Life Cycle Cost) which is the total cost throughout its sum of OICC and OLC), and it is discussed and proposed as one kind of LCC as the following Eq.4.3.

$$OLCC = OICC + OLC \quad \cdots\cdots \quad \text{Eq.4.3}$$

Here, OLCC: Objective life cycle cost relating to heightening in this paper

OICC (Objective Initial Construction Cost): Initial construction cost relating to the expanded structural core

OLC (Objective Loss cost): Water price leaked from the heightened dam

Meanwhile, the Objective Initial Construction Cost (OICC) in Eq.4.3 means that the construction cost was considered only for the cross-section of the expanded structural core except for the all dam cross section. If the construction cost applied to all dam cross section, the construction cost may make in large cost differences, and it is hard to estimate the calculation to find an optimum structural core due to the scale differences in cost.

Therefore, the objective life cycle cost (OLCC) between Case 1 and Case 4 is discussed to judge the optimum structural core in this paper. In addition, Objective Loss Cost (OLC: leakage loss cost) was assessed with respect to the Objective Initial Construction Cost (OICC)-incurred by expanded structural core, and an Life Cycle Cost (LCC) analysis to identify the optimal scale of the expanded core was conducted. In that context, Figure 4.1 shows the concept of objective life cycle cost (OLCC) subjected in this paper.

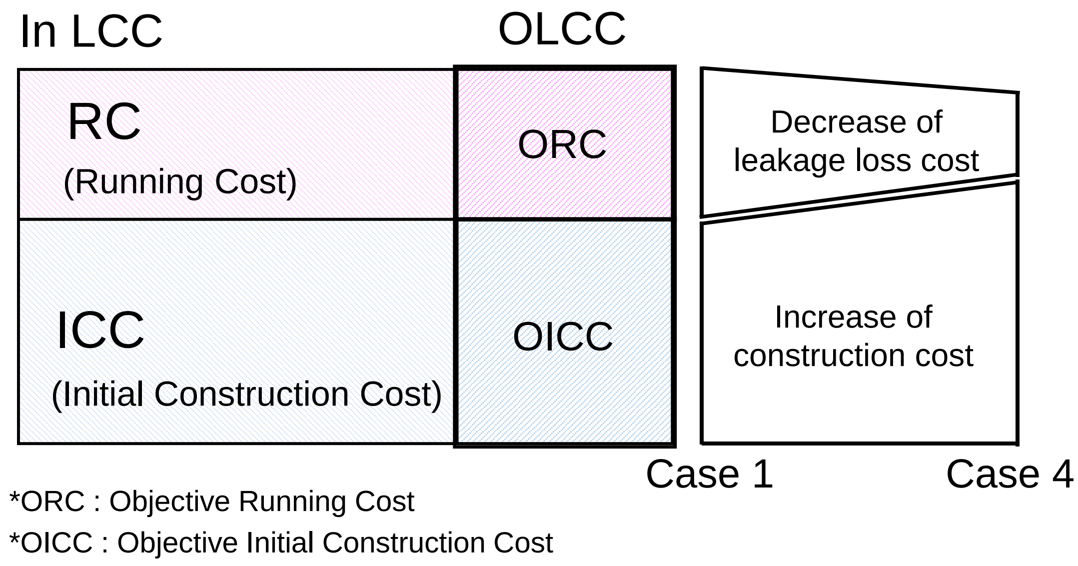


Figure 4.1 Concept of Objective Life Cycle Cost (OLCC)

4.3 Estimation of Objective Initial Cost and Running Costs

4.3.1 Investigation of water price range

To estimate the OICC (Objective Initial Construction Cost) and the ORC (Objective Running Cost = OLC: Objective leakage cost) as described above, the water price range was investigated as first step. The evaluation of water value undertaken shows flexible trends due to changes in regional features, the water management environment, and the seasonal and weather conditions; a comprehensive estimate of water price that can be practically compared to increase of water value by elapsed time is thus required. Based on the foregoing details, in this paper a range of water prices for general water use, and dam water in South Korea as an examples are comprehensively investigated as shown in Table 4.1 (Daejeon city hall, 2014; KWRC, 2014)[5-6]. In regard to this, the water prices the investigated at present time can be compared to the future water price-induced by the economic efficiency analysis, and this provides the information of the leakage loss cost in relation to the consideration of potential changes according to the low water prices in South Korea. Figure 4.2 illustrates the trends of water prices used for each item, showing that most water prices range between 223 and 775 won/m^3, and the water price for irrigation use subjected in this paper was appeared as the lowest one (50.3 won/m^3).

Table 4.1 Range of water prices according to the purpose of use [5-6]

Division	Item	Water price (won/m^3)
Water supply (Daejeon City Hall, 2014)	Domestic use	560
	General water use	730
	Bathwater use	630
	Industrial use	775
Sewerage (Daejeon City Hall, 2014)	Domestic use	390
	Business use	450
	Commercial use	520
	Bathwater use	440
	Industrial use	490
Dam water (Kore Water Resource Corp., 2014)	River water	223
	Precipitated water	313
	Purified water	413
	Irrigation use etc	50.3

*Standard currency: USD 1.0 per cubic metre: KRW 1,079cubic metre 2015
JPY 1.0 per cubic metre: KRW 9.30 cubic metre, 2015

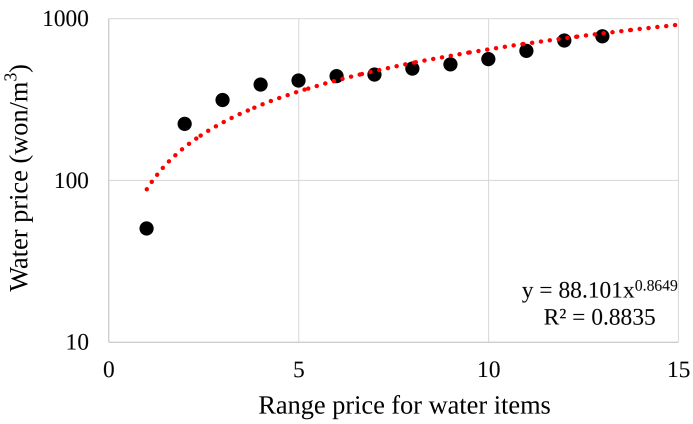


Figure 4.2 Trends of water prices for each item in South Korea

4.3.2 Estimation of Objective Initial Construction Cost and Objective Running Cost

To estimate the Objective Initial Construction Cost (OICC) and the Objective Running Cost (ORC), this section outlines the conditions of application and the economic evaluation method for Objective Life Cycle Cost (OLCC).

In connection to the economic evaluation method, the net present value method (NPV), which is among the general economic evaluation method used for selecting efficient businesses, calculates the flow of net profit obtained until the final year of business by the investment business at the present value. However, as described above, general water prices in South Korea, the change cycle of the inflation rate may be thus predicted to be faster because the water price (unit price of water supply and sanitation services to households, including taxes, OECD 2007-08 Survey)[1] of South Korea is relatively high compared with those of OECD member countries in the last 10 years (OECD, 2010). In this regard, if the water value in South Korea is estimated by using the NPV method, the water price may drop below the initial water price of the present time because of the application of discounts according to the number of years; consequently, Objective Life Cycle Cost (OLCC) calculated from the expanded structural core may be underestimated.

Therefore, Objective Running Cost (ORC = OLC: leakage loss cost) was estimated based on the compound interest method as shown in Eq. 4.4 by considering potential fluctuations in inflation rates (r) and exponentially increasing water values in relation to future climate warming. Here, South Korea's average inflation rate (3%) was applied by considering the inflation target range of 2.5–3.5% set by the NABO in 2013 [2].

Meanwhile, the number of limitation years (n) applied to Objective Life Cycle Cost (OLCC) was 60 years based on the ongoing period of the use of a reservoir dam evaluated by the Korea rural community corporation (KRC). Here, there is also a reservoir dams which have elapsed 60 years already but this study applied 60 years as representative value considering the differences of the environment of management in each reservoir.

$$\mathrm{ORC} = \mathrm{A} \times \sum_{n=1}^{60} \frac{(1+r)^{n}-1}{r} \cdots\cdots\cdots\cdots\cdots\cdots \text{Eq.4.4}$$

Here, ORC (Objective Running Cost: leakage loss cost): Sum price of water leaked during life time of dam (60 years) (see Eq.4.3)

A: Price of water leaked in first year

n: Number of passed year after completing heightening work

r: Inflation rate (3%)

For objective initial construction cost (OICC), it was based on the current construction material cost (CMC) and construction work cost (CWC) as shown in Eq. 4.5.

$$\mathrm{OICC} = \mathrm{CMC} + \mathrm{CWC} \cdots\cdots\cdots\cdots\cdots\cdots \text{Eq.4.5}$$

Here, OICC (Objective Initial Construction Cost): Initial construction cost relating to expanded structural core (see Eq.4.3)

CMC (Construction Material Cost: embankment, core, sand): Material cost only relating to construct the expanded structural core

CWC (Construction Work Cost: fill up, compaction, excavation): Construction cost only relating to the expanded structural core

4.3.3 Calculation of Objective Initial Construction Cost

In this section, an actual heightened dam for inclined-type model (Case 1: Gyeryong reservoir prior to the expanded core construction) was used to calculate the construction material cost (CMC included embankment, core, sand) and construction work cost (CWC included fill up, compaction, excavation) by considering the variation range of the construction cross section due to the expanded scale of the core (standard of construction estimating: Korea, 2012)[7)]. Figure 4.3 shows the Conceptual figure of construction cross section of each model (Cases 1–4) calculated by estimating the Objective Initial Construction cost (OICC). The details of the construction cross sections changed by the expanded scale of the core include a decrease in the cross sectional area of the new filling material and an increase in the extent of excavation on the upper part of the existing dam. The excavated cross sectional area was filled by new filler material; accordingly, the construction cost incurred because of the filler material increased. Table 4.2-4 shows the calculated values of the construction material cost (CMC) and construction work cost (CWC) incurred by the expanded core at the core joint. Table 4.5 outlined the construction cross section (Cases 1–4) based on the Figure 4.3 (blue line: position which the construction cross section was changed by scale of core expansion). Here, in the cost, for every 1 m^3 based on the value of Case 1 that includes the material, fill-up and compaction, the filter material (22,163 won/m^3) is approximately 1.6 times more expensive than the core material (14,144 won/m^3) and 1.8 times in embankment material (12,017 won/m^3); however, when considering the changes in the construction cross sectional area (including the dam length 300m) due to the expanded scale of the core, the construction cross sectional area (2,793 m^3) of the core is approximately 4.7 times wider than that of the filter (600 m^3) and about 3.8 times in embankment (744 m^3) compared to Case 4, as shown in Table 4.5. Table 4.6 presented the total cost that includes the material, fill-up and compaction in considering the change in construction cross section (Case 1-4) presented in Table 4.5, Figure 4.4 shows the trend of total cost (material, fill-up, and compaction cost) of each Case considering the all construction cross section (excavation cost were ignored because it is very few amount compared to material cost).

As a result, it can be found that the construction cost (sum of material, fill-up and compaction) for the core is approximately 3 times higher than that of the filter in comparison with Case 4. This can be explained by the fact that the estimation of the core price based on the economically feasible optimum core scale is an important construction variable.

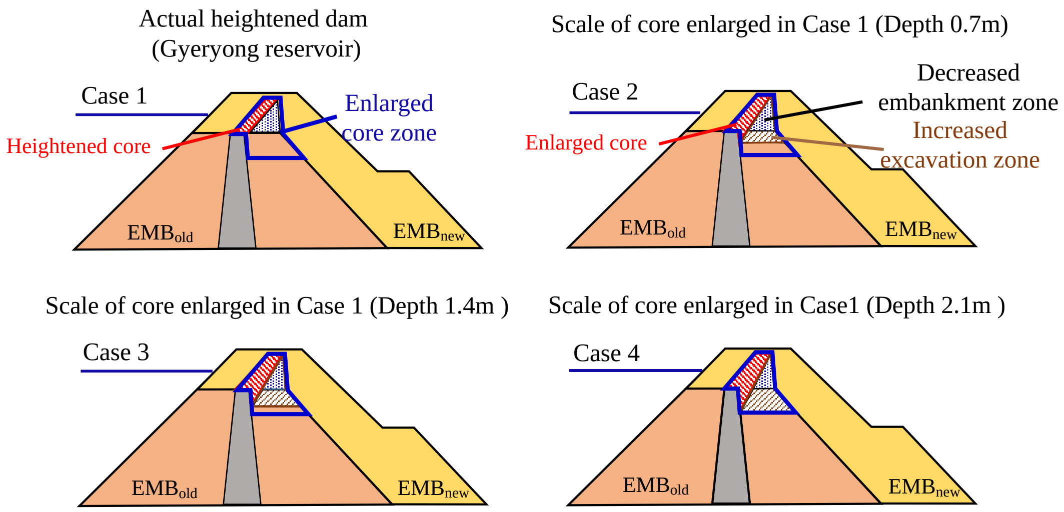


Figure 4.3 Conceptual figure of construction cross section of each model (Cases 1–4) calculated by estimating the Objective Initial Construction Cost (OICC)

Table 4.2 Construction Material Cost (CMC) and Construction Work Cost (CWC)

Division	Items	Unit	Material cost	Labor cost	Outside order cost	Total
Materials (CMC)	Embankment	won/m^3	1,630	862	1,044	3,536
	Core (clay)	won/m^3	2,647	1,384	1,681	5,712
	Filter (sand)	won/m^3	16,528	3,540	1,707	21,775
Fill-up (CWC)	Embankment	won/m^3	175	96	117	388
	Core (clay)	won/m^3	207	114	139	460
Compaction (CWC)	Embankment	won/m^3	218	7,694	181	8,804
	Core (clay)	won/m^3	802	6,689	481	7,972
Excavation (CWC)	Embankment	won/m^3	276	152	185	613

Table 4.3 Sub-total for sum of CMC and CWC

Division	Unit	Sub total of construction cost (won/m^3)	
		Materials+Fill-up +Compaction	Excavation
Embankment zone	won/m^3	12,017	613
Core zone	won/m^3	14,144	-
Filter zone	won/m^3	22,163	613

Table 4.4 Total amount of Objective Initial Construction Cost (OICC)

Division	Construction cross section (won/m^3)						Total amount of construction cost OICC (won)
	Materials+Fill-up+Compaction A_1 (m^2)			Excavation A_2 (m^2)			
	Core	Embankment	Filter (sand)	Core	Embankment	Filter (sand)	(Construction cost×(A_1 +A_2)) ×(Dam length, 300m)
Case 1	11.76	11.76	7.84	-	0	0	144,423,384
Case 2	13.72	12.25	8.82	-	3.43	0.49	161,743,365
Case 3	17.15	12.74	9.31	-	7.84	0.98	182,223,111
Case 4	21.07	14.21	9.8	-	13.72	1.47	208,585,356

Table 4.5 Construction cross section calculated on the basis of Case 1 (See Figure 4.4)

Division	Construction cross section considering the dam lengh (m^3)					
	Materials+Fill-up+Compaction A_1 (m^2) ×(Dam length, 300m)			Excavation A_2 (m^2)×(Dam length, 300m)		
	Core	Embankment	Filter (sand)	Core	Embankment	Filter (sand)
Case 1	-	-	-	-	-	-
Case 2	588	74	294	-	1,029	147
Case 3	1,617	294	441	-	2,352	294
Case 4	2,793	744	600	-	4,116	441

Table 4.6 Total cost in each material considering the cross section
(Including the entire dam length 300m)

Division	Cost that includes material, fill-up and compaction (won)					
	Cost that includes material, fill-up and compaction (won/m^3)			Total cost in considering construction cross section (won)		
	Core	Embankment	Filter (sand)	Core	Embankment	Filter (sand)
Case 1	14,144	12,017	22,163	-	-	-
Case 2				8,316,672	883,250	6,515,922
Case 3				22,870,848	3,532,998	9,773,883
Case 4				39,504,192	8,940,648	13,297,800

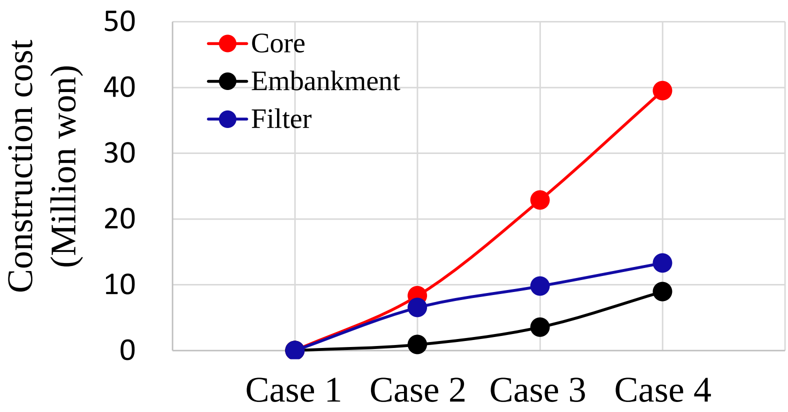


Figure 4.4 Trend of the cost (sum of materials, fill-up, and compaction cost) in each Case based on the changes by construction cross section (including the dam length 300m)

4.3.4 Trend in leakage water price by elapsed time

The price applied to the value of leakage water price was the lowest (50.3 won/m^3) in the range in which the current water prices are investigated in the Table 1, which corresponds to the dam water utility price. Figure 4.5 shows the relationship between the leakage water price and the construction cost of the core heightened dam by elapsed time of 10, 20, 30, 40, 50 and 60 years after the heightening works; the inclination for each number of years implies that the design efficiency increases as the range of construction cost increases. In this regard, the absolute value of the inclination in leakage water price of Case 4 compared to that of Case 1 grows by elapsed time with regard to the construction cost; thus, the leakage water price of 60 years is favorable for efficient design in this study. Based on the results obtained from Figure 4.5, the changes for the value of leakage water price by elapsed time is shown in Figure 4.6. The value of leakage water price may be very small depending on the scale of each core in the graph; however, in terms of reuse and the stability of the existing reservoir dam, this difference is expected to increase in range when considering the long-term economic value of leakage water price and the increase in water prices. In regard to this, if the differences of leakage water price by elapsed time (10-60 years) were considered based on each model (Case 1-4), the absolute value of the inclination of Range I (Case2-3) have relatively gentle compared to that of Range II (Case1-2) or Range III (Case 3-4) as shown in Figure 4.7.

To understand about the trend of inclination presented in Figure 4.7, the inclination of each Case obtained from inflection point for trend equation were partially differentiated as shown in Figure 4.8. Though the excavation depth for expanded structural core in each model (Case 1-4) is the same with 0.7m respectively, as shown in Figure 4.3, the differences of leakage water price appeared a different value for each model. As a result, the Range III (Case3-4) can be favored economically in terms of the leakage loss value by elapsed time because the interval difference (red line: Figure 4.8) from Case 3 to Case 4 is larger than that of Range I or Range II. Meanwhile, the increments of construction costs for each models (Cases 1–4) shown in Figure 4.6 increase because of the increased construction cross-section of filter material and core with the expanded core scale. Figure 4.9 shows the results of normalization based on the Case 1 with regard to the construction cost and increments in construction cost for 60 years elapsed. The trend of the construction cost shows nonlinear increments according to the expanded scale of each core. This can be explained that the construction cost may geometrically increase, as the expanded scale of the core widens.

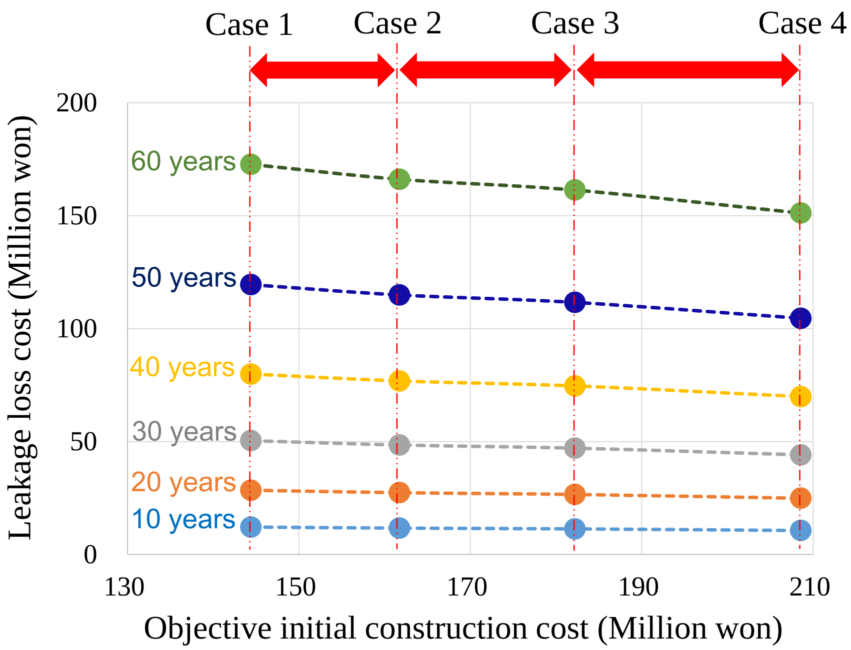


Figure 4.5 Relation between the objective loss cost (OLC: leakage loss cost) and the objective initial construction cost (OICC) by elapsed time

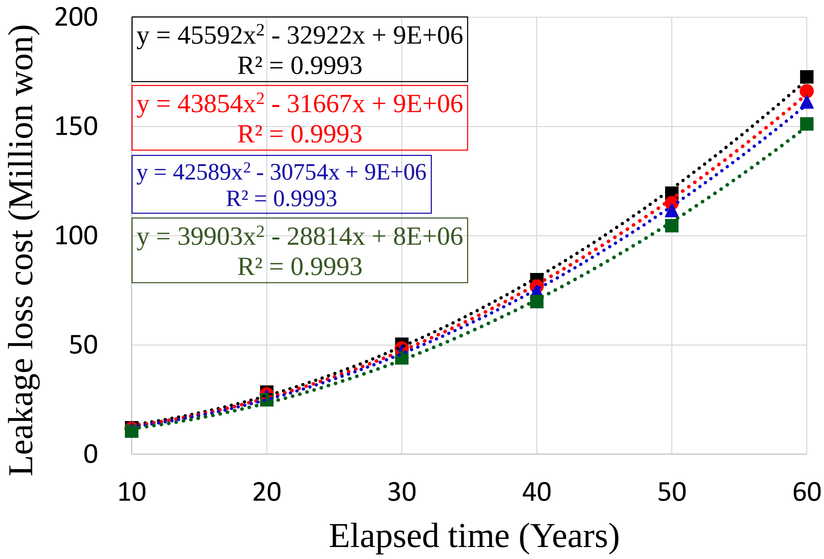


Figure 4.6 Value of objective loss cost (OLC: leakage loss cost) according to the changes in the number of years elapsed

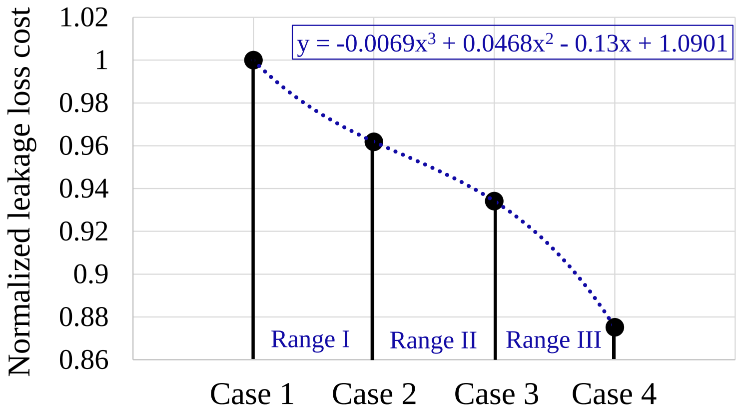


Figure 4.7 Normalized leakage loss cost according to each model (Case1-4)

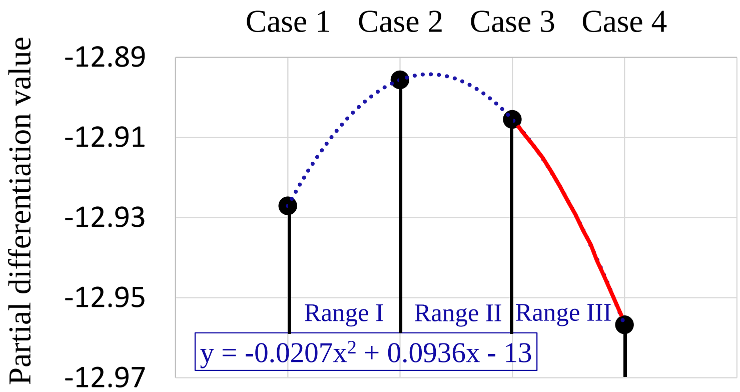


Figure 4.8 Result of partial differentiated trend line obtained in Figure 4.7

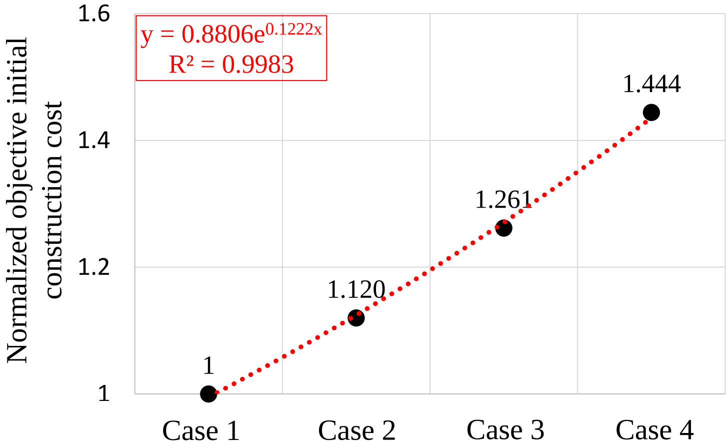


Figure 4.9 Increments of objective initial construction costs (OLCC) for the models of (Case1-4)

4.4 Objective Life Cycle Cost (OLCC) in Relation to Water Price Range

The core heightened dam applied to the expanded structural core construction method has improved structural stability with respect to permeable and seismic problems as described the result obtained in the seepage flow analysis and dynamic response analysis. On the other hand, after a long passage of time, the construction-leakage water price according to the core scale can change in the reservoir due to the fluctuations in water prices. In this regard, this section proposes a water price range that considers an effective design efficient for the optimum scale of the core joint structure by objective life cycle cost (OLCC). First, the estimated results from section 4.3.2 and 4.3.3 were outlined. Table 4.7 (133 won/m^3), 8 (150 won/m^3), 9 (168 won/m^3) and 10 (215 won/m^3) lists the results in relation to the Objective Initial Construction Cost (OICC) and Objective Loss Cost (OLC: leakage loss cost) obtained by the expanded scale of core, respectively.

Table 4.7 Results obtained from the calculation of OICC and OLC, (133 won/m^3)

Water value - 133 won/m^3				
TYPE	Leakage quantity (m^3/day)	Initial leakage loss cost (m^3/won/ year)	Objective loss cost (OLC: leakage loss cost) (m^3/won/60 years)	Objective initial construction cost (OICC) (won)
Note	Analysis results	Leakage×water price×365 days	ORC= $A\times \sum_{n=1}^{60} \frac{(1+r)^n-1}{r}$	CMC + CWC
Case1	57.70	2,801,047	456,720,258	144,423,384
Case2	55.50	2,694,248	439,306,314	161,743,365
Case3	53.90	2,616,576	426,641,628	182,223,111
Case4	50.50	2,451,523	399,729,169	208,585,356

Table 4.8 Results obtained from the calculation of OICC and OLC, (150 won/m^3)

Water value - 150 won/m^3				
TYPE	Leakage quantity (m^3/day)	Initial leakage loss cost (m^3/won/ year)	Objective loss cost (OLC: leakage loss cost) (m^3/won/60 years)	Objective initial construction cost (OICC) (won)
Note	Analysis results	Leakage×water price×365 days	ORC= $A\times \sum_{n=1}^{60} \frac{(1+r)^n-1}{r}$	CMC + CWC
Case1	57.70	3,159,075	515,098,036	144,423,384
Case2	55.50	3,038,625	495,458,249	161,743,365
Case3	53.90	2,951,025	481,174,768	182,223,111
Case4	50.50	2,764,875	450,822,371	208,585,356

Table 4.9 Results obtained from the calculation of OICC and OLC, (168 won/m^3)

Water value - 168 won/m^3				
TYPE	Leakage quantity (m^3/day)	Initial leakage loss cost (m^3/won/ year)	Objective loss cost (OLC: leakage loss cost) (m^3/won/60 years)	Objective initial construction cost (OICC) (won)
Note	Analysis results	Leakage×water price×365 days	ORC= $A\times \sum_{n=1}^{60} \frac{(1+r)^n-1}{r}$	CMC + CWC
Case1	57.70	3,538,164	576,909,800	144,423,384
Case2	55.50	3,403,260	554,913,239	161,743,365
Case3	53.90	3,305,148	538,915,741	182,223,111
Case4	50.50	3,096,660	504,921,056	208,585,356

Table 4.10 Results obtained from the calculation of OICC and OLC, (215 won/m^3)

Water value - 215 won/m^3				
TYPE	Leakage quantity (m^3/day)	Initial leakage loss cost (m^3/won/ year)	Objective loss cost (OLC: leakage loss cost) (m^3/won/60 years)	Objective initial construction cost (OICC) (won)
Note	Analysis results	Leakage×water price×365 days	ORC= $A\times \sum_{n=1}^{60} \frac{(1+r)^n-1}{r}$	CMC + CWC
Case1	57.70	4,528,008	738,307,185	144,423,384
Case2	55.50	4,355,363	710,156,824	161,743,365
Case3	53.90	4,229,803	689,683,835	182,223,111
Case4	50.50	3,962,988	646,178,732	208,585,356

In the calculation process, after applying the water price (1 m^3) to the water leakage quantity (1 m^3/year) obtained from the analysis results considering the dam length (300m) (Lee et al, 2014), the design efficiency was evaluated by combining the objective initial construction cost (OICC) and objective loss cost (OLC: leakage loss cost) obtained from the results of Eq. 4.1 considering 60 years. Figure 4.10 shows the total sum of OICC and ORC shown in Table 4.7-10. Figure 4.11 shows the remodeling of the extended efficacy (Total sum for OLCC).

As a result, the range of water price, which increases the OICC and OLC efficiencies with regard to changes in the expanded scale of the core, was effective at minimum 133 to maximum 215 won/m^3. Here, the maximum value (215 won/m^3) was established under the condition in which the rates of efficiency of Case 2 and Case 3 was the same, because the rates of efficiency of Case 4 can be overestimated when the rates of efficiency of Case 2 is lower than that of Case 3. Table 4.11 represents the range of water price that considers the construction-leakage water price with the trend line of design efficiency for core expansion. As an economic evaluation method, it is based on the Cases, that have the same rates of efficiency or lower than that of Case 1 (blue line:

OLCC of Case 1), having an economic feasible for a long-term that can contribute to the stabilization of the heightened dam shown in Table 4.11.

As the analysis result, it was expected that for the water prices from 133 to 149 won/m^3, Case 2, which has the same rate of efficiency as Case 1 or lower than that, can contribute to the stabilization of the heightened dam.

The efficiency in Case 2 is the lower with regard to the water prices from 150 to 157 won/m^3; however, Cases 4 is also considered for heightening plan in the site because the model of Case 4 has the same design efficiency as Case 1 or lower than that.

In the range of water price from 158 to 167 won/m^3, the design efficiency is considered as the high order of Case 4 and Case 2, especially the model of Case 4 is recommended as the best in perspectives of structural reinforcement of core joint.

In the range of water price from 168 to 215 won/m^3, the design efficiency appeared as the highest order of Case 4, Case 2 and Case 1, wherein these results can be considered, the construction budget or the plan for downstream site usage can be determined based on the dam heightening plan of the site. When the water price is higher than 216 won/m^3, the design efficiency of Case 4 has the lowest rate of efficiency, it is expected to have economic advantages regarding the inflation of water price in the future.

Meanwhile, the recommended model by the objective life cycle cost (OLCC) is related to the initial construction cost, it is thus important to find the standard range of water price. In regard to this, the standard range of water price was decided based on the range of water price (157-158 won/m^3), which was divided by Case 2 and Case 4 with respect to the highly recommended model in each Case. Furthermore, because the water price range of 133–215 won/m^3 has a realistically similar range to the present price of dam use water (50.3 won/m^3) presented by Korea water resources Corp., it is expected to be used as a reference in the heightening work and core reinforcement plan, which considers the future economic value of leakage water price and fluctuations in water prices in South Korea.

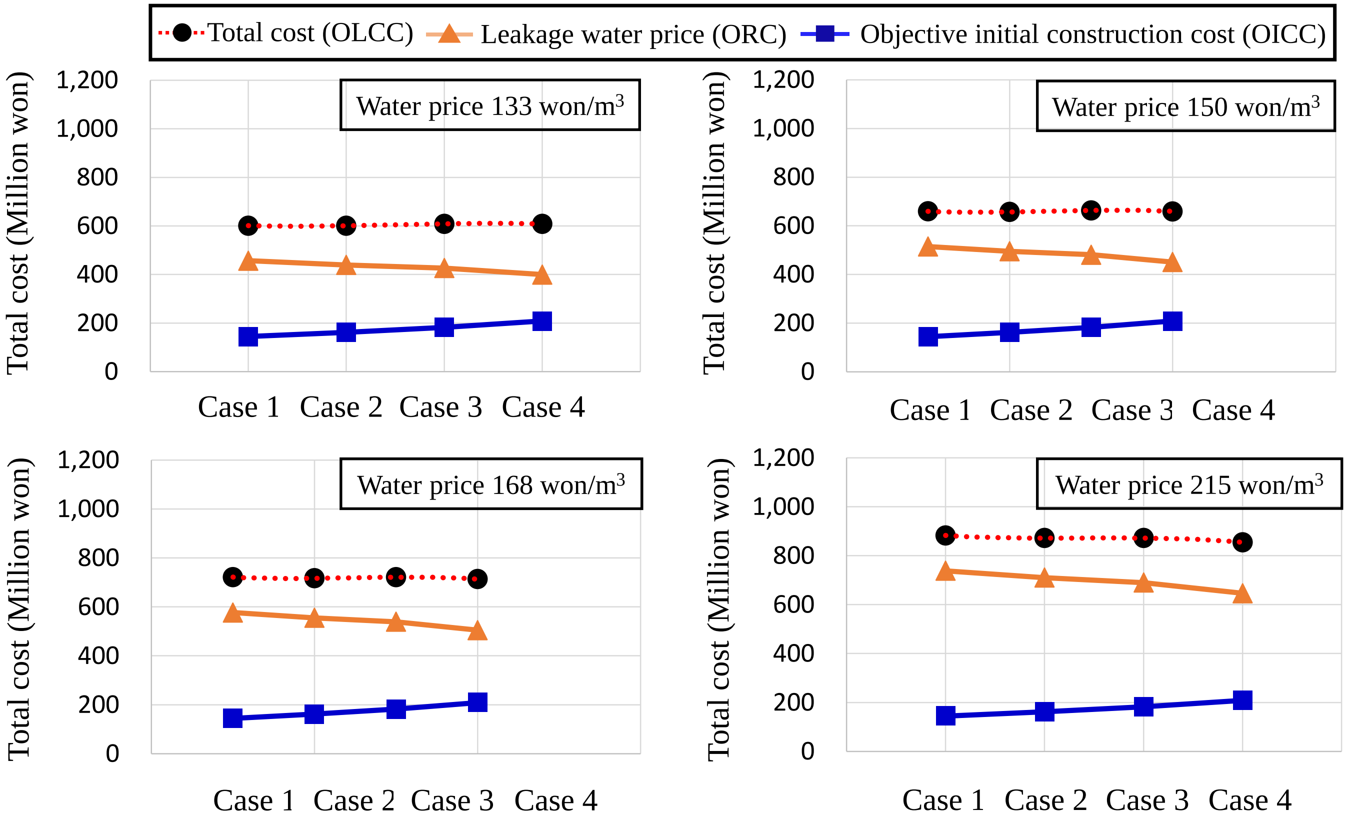


Figure 4.10 Total sum (OLCC) of objective initial construction cost (OICC) and objective loss cost (ORC)

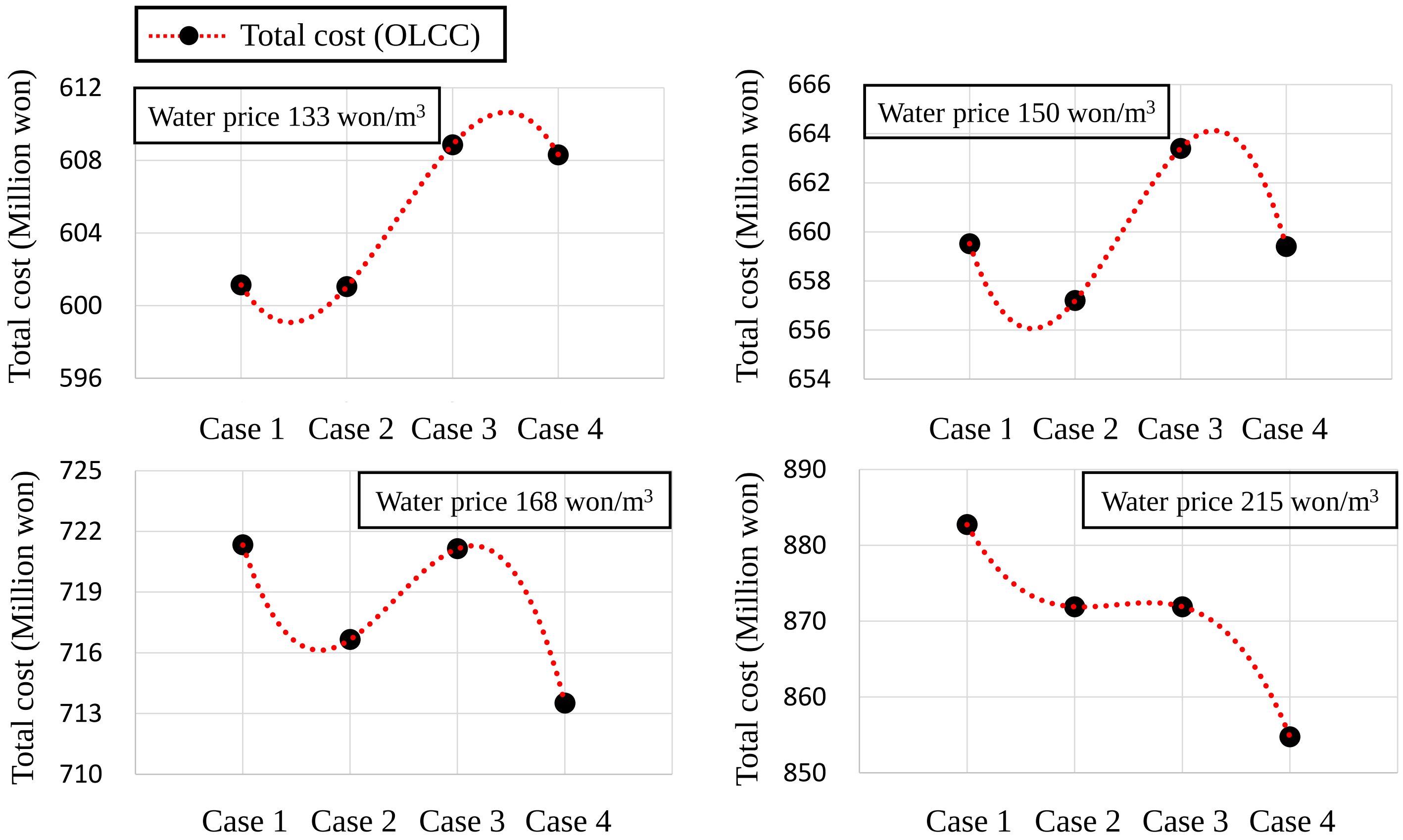
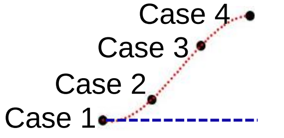
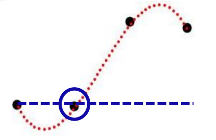
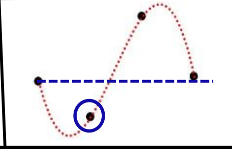
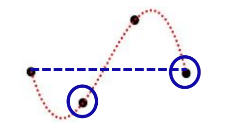
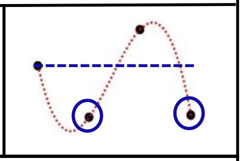
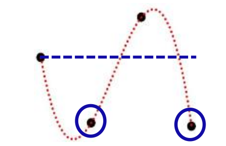
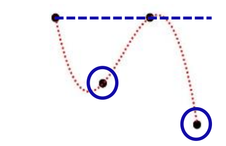
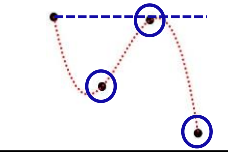
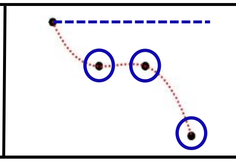
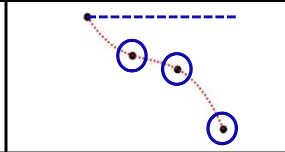


Figure 4.11 Total cost for OLCC

Table 4.11 Comparison of OLCC in each Case and decision of the optima design

Water price	Less than 132 won/m^3	133-149 won/m^3		150-157 won/m^3	
Correlation of OLCC in each Case					
Recommend for optima core scale	Case 1	Case 2		① Case 2 ② Case 4	

Water price	158-167 won/m^3		168-215 won/m^3		More than 216 won/m^3
Correlation of OLCC in each Case					
Recommend for optima core scale	① Case 4 ② Case 2		① Case 4 ② Case 2 ③ Case 3		① Case 4 ② Case 3 ③ Case 2

---- OLCC of Case 1

4.5 Summary

In this chapter, this study was performed to propose the optimal scale of the core joint structures by the expanded structural core construction method. To evaluate the economic feasibility of expanding the scale of the core, the objective life cycle cost (OLCC) as kinds of concept of the life cycle cost (LCC) was proposed and discussed, for the optimum design of the expanded structural cores that can be economical in the long run with respect to the rational construction cost. The following are the summary.

(1) In the value of leakage loss by number of years, the absolute value of the slope grows with the passage of the time; the water value of 60 years in the scope of this study is favorable. The core heightened dam applied to the expanded structural core in relation to future climate change can have an economic effect in terms of reuse, as well as the structural safety with a decrease of the water leakage in the long run.

(2) The total partial initial construction cost for the sum of the construction material cost (CMC) and the construction work cost (CWC) has a nonlinear increments as the expanded scale of the core widens.

(3) The optimal scale of the expanded structural core evaluated in the objective life cycle cost (OLCC) was changed by the value of water price, and the result is obtained that the optimum scale of the core investigated in this study is economically valid with relation to the future water value.

From the result, the optimal scales of expanded structural core for economic feasibility can be discussed throughout the proposed evaluation method that can minimize the total sum of construction cost and leakage water price considering 60 years elapsed after heightening construction work.

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CHAPTER 5

CONSCLUSIONS AND REMARKS

5.1 Conclusion

As the given role of the core in resisting the upstream water pressure is to keep the safety of the dam, the core is the most important structure in dams. In regard to this study, since the new core (inclined-type) is heightened in the upper part of the vertical core of the existing dam, the core joint zone between the heightened core and the existing core can be a vulnerable part to permeable problems. In addition, the core deformation and/or cracks induced by compressive stress from earthquakes can be bigger around the core joint, and these can cause the increase of the treatment cost related to repair and/or reinforcement. Thus, the core joint zone of the reservoir dam can be vulnerable to permeable (concentrated infiltration and backward erosion piping) and seismic (core deformation and cracks) behaviors since the water level of the reservoir has constant variability all year around.
In this study, therefore, an expanded structural core construction method as concept of the core reinforcement method in the core heightened dam by inclined-type was proposed and evaluated on permeable and seismic behaviors. In addition, optimum design of the expanded structural cores that can be economical in the long run was discussed with respect to the rational construction cost. The conclusions in each chapter are outlined as follows.

In chapter 2

This chapter was performed to investigate the expanding effects of the expanded structural core on seepage characteristics by using FEM seepage flow analysis method. To identify the seepage characteristics as described above, the four kinds of model which was proposed in this paper were applied. The results obtained in the seepage flow analysis were outlined as follows.

First, the piping inspection in the downstream slope was evaluated by seepage quantity and hydraulic gradient. As a result, the piping revealed that the seepage quantity and hydraulic gradient was reduced according to scale increase of the expanded structural core, thus, piping safety standards were met in all expanded structural core proposed in this study, and thus, the risk of the core expansion-induced piping is extremely low.

Second, the seepage line that occurred in downstream-side dam body was evaluated to understand the impact on the core heightened dam for inclined-type. As a result, the height of the seepage line in the downstream dam body decreased gradually as the expanded scale of the core increased. According to the result, there has been a difference of about 0.4 m between the highest one and the lowest one. This implies that the decrease of the height of the seepage line has an effect to reduce the erosion area that can be caused by infiltration.

Third, the expanding effects of the core were considered in details as the flow velocity at the core joint and the change of seepage quantity passing through the heightened core for inclined type (approximately length 10 m) on the scope around the core joint zone. From the results, the decreased range in the flow velocity with respect to actual heightened dam (Case 1) showed the ranging from 1.06 (Case 2: lowest one)-1.77 (Case 4: highest one) times, and the ranging from 1.07 (Case 2: lowest one)-1.52 (Case 4: highest one) in the quantity of the seepage passing through the inclined-type core. These results are closely associated with the increase of the back water distance of the core width that controls the seepage water. Therefore, it is expected that the core joint can be reinforced by the expanded structural core as means to reduce soil erosion velocity in relation to the core that was constructed as the narrow core width (1.5-3m) of a reservoir.

Fourth, the saturation characteristics of the core under the conditions of water drawdown were considered by performing the seepage flow analysis, to the scope around the core joint zone. As a result, the core zone containing residual moisture under water drawdown gets wider as the expanded scale of the core increased. This implies that the increase of the zone containing residual moisture of the core can reduce possible damages associated with core cracks or deformations since a low-saturation material has greater vulnerability to shear deformation than a high-saturation material. Therefore, it is expected to have reinforcement effects in enhancing the seismic performance of a core heightened dam by inclined-type.

Last, the available range of coefficient of permeability proposed for the heightened core was discussed. Specifically, since the water pressure acting on the heightened core (k_{new}) is relatively low compared to the core placed at the bottom side (k_{old}), the coefficient of permeability for heightened core can be designed in a manner to enhance the efficiency related to the construction cost and work process. As a result, the available range of coefficient of permeability for the heightened core can be alleviated through the required performance for the heightened dam planed within the allowable leakage water. Thus, it is expected to improve the heightening work efficiency, since the area of the borrow pit around the reservoir available for core construction is wide.

In chapter 3

This chapter was performed to investigate the expanding effects of the expanded structural core on seismic effects by using FEM dynamic response analysis. To identify the dynamic characteristics in the same way as in the seepage flow analysis, the four kinds of model were applied. The results obtained in the dynamic response analysis were outlined as follows.

First, the natural periods of the heightened dam was investigated to understand the impacts on the expanded scale of the structural cores. As a result, there were no perceivable changes in each expanded scale of the core, thus the heightened dam applied to the expanded structural core construction method proposed in this study will not be affected.

Second, the dynamic behavior (distribution of the shear stress) on the expanded scale of the structural cores was evaluated by input sinusoidal wave based on the result obtained in the natural period analysis. At first, the dynamic response analysis was focused on the differences of the response directions (upstream and downstream-side of the reservoir) by input sinusoidal wave to identify the impact on heightened core by inclined-type. As a result, the shear stress acting on the core joint is more affected by the response on downstream-side direction than that of the response on the upstream-side direction. This implies that the response on the downstream direction tends to be deformed easily.

Third, the dynamic behavior (distribution of the shear stress) on the expanded scale of the structural cores was evaluated by input seismic motions based on the result obtained in input sinusoidal wave. As a result, the shear stress acting on the downstream-side dam body was greater in all seismic motions (seismic motions and its inversed seismic motions). This may be ascribed to the structural core being tilted toward the downstream side where the downstream-side embankment zone (silt and sand) is compressed. This implies that the core placed in the downstream-side can be influenced by the damage related to the core deformation and cracks during earthquakes. In addition, the shear stress that occurred in the core joint subjected in this study was decreased gradually in all seismic motions (seismic motions and its inversed seismic motions) according to the expanded scale of the core, thus, it is expected to be enhanced on the seismic performance of a core heightened dam by inclined-type.

In chapter 4

This chapter was performed to investigate the optimum structural cores based on the results obtained in the seepage flow analysis and the dynamic response analysis for identifying the expanded effect of the core joint. Here, the reinforcement effects on the core joint zone on permeable and/or seismic problem were improved, but as the expanded scale of the core increased, the construction cost also increased. Accordingly, the optimal scale of the structural core must be determined based on the assessment whether the expanded scale of the core is economic as means to guarantee the rational construction cost in relation to the heightening work. In regard to this, the concept of the OLCC (Objective Life Cycle Construction Cost) which is defined as the sum of the partial initial cost and one kind of loss of benefit (value of leakage water price during life cycle of dam) for the expanded structural core in this paper was proposed, and it was evaluated with respect to the value of water price that was estimated for n years. The results obtained in the economic efficiency analysis were outlined as follows.

First, the objective loss cost (OLC: leakage loss cost) for each scale of the expanded structural core for n years was estimated. As a result, the value of the leakage water price in all expanded scale of the structural cores is high by elapsed time, and large differences appeared between the actual core structure (prior to expanding a core) and the expanded scale of the structural core. Therefore, the core heightened dam applied to the expanded structural core in relation to future climate change can have an economic effect in terms of reuse, as well as the structural safety with a decrease of the water leakage in the long run.

Second, the objective initial construction cost (OICC), which was made on the scope of a core subjected in this study, in each scale of the core expanded structural core was evaluated. As a result, the total partial initial construction cost for the sum of the construction material cost (CMC) and the construction work cost (CWC) showed nonlinear increments as the expanded scale of the core increased. This implies that the expanded structural core having an optimal configuration in terms of rational construction cost should be established.

Third, the optimum scale of the expanded structural core was proposed by evaluating the objective life cycle construction cost (OLCC) based on the value of water. As a result, the optimal scale of the expanded structural core investigated in the OLCC was changed by the value of water price, and it is valid economically since it can minimize the sum of the construction cost and the leakage water price regarding the future heightening work. Therefore, the optimal scale of the expanded structural core can contribute to the stabilization of the core heightened dam by inclined-type in long run, and it is expected to be payable as a means to reduce the water leakage considering the rise in the price of water in the future.

5.2 Future Research Challenge

On the basis of the results investigated in this study, the future research challenges are as follows.

1. Study on Sensitivity Analysis for Erosion of Structural Core Joint
2. Seepage Characteristics on Correlation between Old Core and New Core in Heightened Dam
3. Guideline on Field Applicability for Alleviated Coefficient of Permeability of Core
4. Proposal on Prediction Method of Value of Water for Irrigation

1. Study on Sensitivity Analysis for Erosion of Structural Core Joint

(1) Flow velocity and seepage quantity in each expanded structural core

With regard to the erosion problem of the core in section 2.3.4, the author evaluated the flow velocity and the quantity in each expanded structural core that has different scales. In comparison with Case 1 and Case 4, the decrease in the flow velocity was 0.56 times and 0.67 times in the quantity of seepage passing through the inclined-type core. From the result, the expanded structural core method is effective to the core joint zone on seepage control but there could be more verification on what they mean in terms of engineering, with regard to the erosion in core joint.

(2) Material characteristics and erosion in structural core

The material characteristic for the structural core of the heightened dam investigated in this study were classified into a low plastic clay (USCS: CL), it has very small clay. In regard to this, the bonding effects within the core were dependent on the quantity of clay particles, and thus the proportion of small differences of clay particles may cause erosion due to non-homogeneity of the core.
In that context, the structural core combined with an existing core and a new one has anisotropy of strength and permeability, and thus the core heightening work that used the existing fill dam need to gain a deeper understanding of the erosion degree that can occur in the core joint. Hereupon, the design specification that can judge the degree of erosion should be established through the erosion experiment according to the mix proportion in each material (clay, silt and sand).

2. Seepage Characteristics on Correlation between Old Core and New Core in Heightened Dam

(1) Relation between hydraulic fracturing and flow velocity

The future research is focusing on the fact that the flow velocity and seepage quantity may be changed by material anisotropy (i.e. strength and permeability) when the water pressure was acting on the structural core. Here, the water pressure is generally related to the water level, but the structural core subjected in this study was combined with old and new cores, and thus this implies that the consideration of the water pressure in terms of material characteristics is necessary. Specifically, since the new core for heightening work is newly constructed, the flow velocity of the old core can be higher than that of the new core, due to low permeability of the new core placed in the upper part-side of the heightened dam. As described above, this study presented some reasons for possible problem that may occur in the old core, as follows.

a) The old core has still the same width even after the heightening work was performed.
(The water pressure acting on the old core increased.)

b) The materials characteristics for core construction was classified into low plastic clay.
(Proportion of silt and sand are very high.)

c) Some old reservoirs dam are included for the heightening work.
(There may exist the decrease of filter performance in the old dam.)

Meanwhile, the general width of the core is designed to be 40% resistant to water pressure. However, if the water pressure exceeds the earth pressure of the existing core, the dam safety may be influenced by the hydraulic fracturing. In regard to this, since a general earth fill-type dam having a core zone has hydraulic fracturing problems, and thus it is expected that the possibility of the hydraulic fracturing become high after dam heightening work. In this regard, the erosion of the old core implies that the necessity of engineering standards for impact on stability of the core heightened dam at present are needed.

3. Guideline on Field Applicability for Alleviated Coefficient of Permeability of Core

In section 2.4, the seepage flow analysis was carried out based on how much the coefficient of permeability for new core can be alleviated. As a result, the predicting equation which can alleviate coefficient of permeability was obtained but the guideline on field applicability was not presented. Therefore, the detailed guideline on field applicability for the alleviated range of coefficient of permeability on the basis of each reservoir environment like water level, allowable seepage quantity, leakage quantity, and rainfall patterns should be established for future use.

4. Proposal on Prediction Method of Value of Water for Irrigation

With regard to the increase of the value of water for irrigation, this study estimated the value of water based on the compound method, but the predicting equation for reliability should be clearly considered all the more. Specifically, the application of the compound method for estimating the water value is effective but the practical use for the dam heightening work can be a problem owing to the big difference of the cost scale on predicting equation.

In short, as the economic estimation of the water value using a compound method depends on the factors like inflow rate, rainfall and temperature, and it has limitation on the way it is applied in simple compound method. Thus, the costs for economic evaluation should be lower than the cost-induced by compound method. The items of the costs can be considered to channel flow for maintenance, water for irrigation, and amount of water evaporation etc., and those costs can be defined into the sum of evaluation costs induced by Life Cycle Cost (LCC).

5.3 Remarks

As described in the conclusions, the expanded structural core construction method proposed in this study is expected to guarantee the life time of the heightened dam in long run, in terms of economic optimization considering the structural safety. In regard to this, the demand for a heightening work securing water resource due to climate change increases over time, the expanded structural core construction method has an outstanding reinforcement effects on permeable and seismic behaviors with an ease of construct ability, and thus it can be expected to be diffused and adopted internationally by Japan and/or developing countries as well as South Korea.

APPENDIX

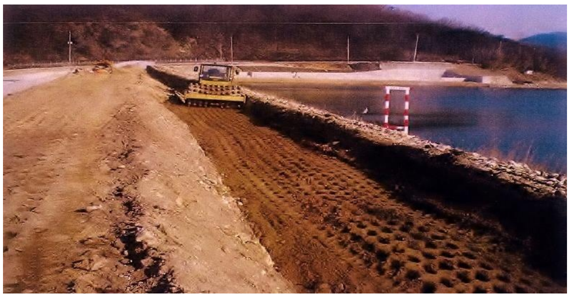
CORE CHARACTERISTICS OF A DAM

A 1.1 Core Heightening Work

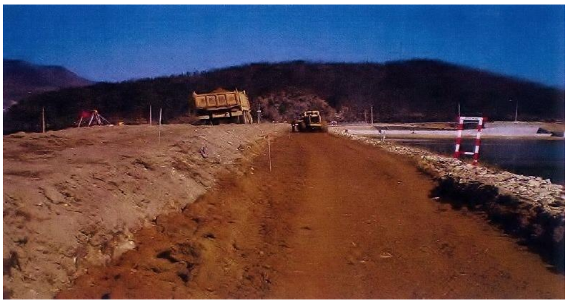
In general, the given role of the core is to keep the safety of the dam, and thus the core construction for dam heightening work has importance. In regard to this, since the core heightening work is performing in running condition, the possible risks even under water drawdown condition should be considered. The following Figures show the core excavation and construction in site of the Gyeryong reservoir.

(a) Removed upper zone of the core

(b) Planed width of the heightened core: about 2m



(c) Compaction work in core zone



(d) Core heightening work

Figure 1 Construction of the core zone that is newly constructed (site: Gyeryong reservoir)

A 1.2 Core Characteristics

As described in section A1.1, the possible risks that may occur in the core heightened dam is dependent on the material characteristics of the core. Table 1-4 presents the soil characteristics related to the component proportion ratio of core materials (clay, silt, sand) in the actual heightened dams. First one shows the Gyeryong reservoir dam subjected in this study and these three dams represent the core heightened dams (each site name; Goemok, Deogyong, and Dorim reservoir in South Korea) around the Gyeryong reservoir. With regard to the soil proportion presented in all Tables, it explains that the clay particle has very small quantity compared to the silt or sand particles. Here, the reason to use small quantity of clay is that the construction of the core can be economic effect if the bonding effects within the core were occurred even in small quantity of clay. From this point of view, this implies that the core having the small quantity of clay particle is likely to be an easy infiltration and/or drainage. Hereupon, the core can be deteriorated by uplift seepage force according to the change of water level of the reservoir and it can cause the increase of the repair/reinforcement cost in the core heightened dam.

Table 1 Gyeryong reservoir

Soils	Clay	Silt	Sand	Gravel	P.I	USCS
Core	12.0%	49.2%	38.8%	-	16.5	CL
EMB	1.5%	13.4%	63.8%	21.3%	-	SM

Table 2 Goemok reservoir

Soils	Clay	Silt	Sand	Gravel	P.I	USCS
Core	17.9%	44.9%	36.2%	1.0%	12.9	CL
EMB	16.0%	23.2%	57.4%	3.4%	7.3	SC

Table 3 Deogyong reservoir

Soils	Clay	Silt	Sand	Gravel	P.I	USCS
Core	18.0%	33.0%	49.0%	-	16.1	CL
EMB	5.7%	22.2%	67.8%	4.3%	12.1	SM

Table 4 Dorim reservoir

Soils	Clay	Silt	Sand	Gravel	P.I	USCS
Core	10.0%	41.5%	48.5%	-	12.9	CL
EMB	1.7%	15.7%	71.5%	11.1%	7.3	SM

*EMB: Embankment