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THE RISK MANAGEMENT OF THERMAL CRACKING FOR CONCRETE DAMS SUBJECTED TO UNPRECEDENTED TEMPERATURE FLUCTUATIONS DUE TO CLIMATE CHANGE*

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SUMMARY

Temperature data used in thermal stress analysis are usually determined on the basis of data accumulated over a period of several tens of years. Because of considerable temperature fluctuations, however, that are thought to be attributable to climate change in recent years, assumed temperature fluctuations have become increasingly greater. Consequently, analytical results tend to deviate from actual concrete conditions so that thermal cracking risk is growing not only in the block under consideration but also at other locations.

To address this problem, therefore, a three-dimensional model covering the entire dam structure including the foundation bedrock is constructed to conduct

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* *Gestion du risque de fissuration thermique des barrages en béton soumis aux variations de température amplifiées par le changement climatique*

thermal stress analysis and determine the thermal cracking index distribution over the entire dam. On the basis of the results thus obtained, multiple blocks having a relatively high probability of occurrence of thermal cracking are identified, and detailed two-dimensional thermal stress analysis is conducted. At the time of concrete placement, changes in concrete temperature are monitored continuously by use of temperature sensors installed in the dam body, and the measurement results are checked against concrete temperature history simulation results based on past atmospheric temperature data. If the temperature difference is greater than predicted, appropriate control measures such as regulation of temperature and cooling can be taken. In the newly developed system, the relationship between the temperature difference between the exterior and interior of dam concrete and the thermal cracking index is determined so that thermal cracking risk can be managed quantitatively by use of the thermal cracking index calculated from the temperature difference.

Keywords: Concrete Dam, Cracking, Temperature Measurement, Automated, Construction, Cooling.

RÉSUMÉ

Les températures ambiantes utilisées pour l'analyse des contraintes thermiques sont en général déterminées à partir des données accumulées pendant des décennies. Ces dernières années, cependant, l'amplification de la variation de température, due probablement au changement climatique, entraîne une variation de plus en plus grande des températures supposées. Par conséquent, les résultats analytiques tendent à s'écarter des conditions réelles du béton, de sorte que le risque de fissuration thermique augmente non seulement dans le bloc considéré, mais aussi à d'autres endroits.

Pour remédier à ce problème, un modèle tridimensionnel couvrant l'ensemble de la structure du barrage, y compris le fondement de la fondation, est construit pour effectuer une analyse des contraintes thermiques et déterminer la distribution de l'indice de fissuration thermique sur l'ensemble du barrage. Sur la base des résultats ainsi obtenus, de multiples blocs présentant une probabilité relativement élevée de fissuration thermique sont identifiés, et une analyse détaillée des contraintes thermiques bidimensionnelles est réalisée. Au moment de la mise en place du béton, les changements de température du béton sont surveillés en permanence à l'aide de sondes de température installées dans le corps du barrage et les résultats de la mesure sont comparés aux résultats de la simulation. Si la différence de température est plus grande que prévu, des mesures de contrôle telles que le maintien de la température adéquate et le refroidissement peuvent être prises. Dans ce système, est déterminée la relation entre d'une part la différence de température entre l'extérieur et l'intérieur du béton et d'autre part l'indice de fissuration thermique, ce qui permet de réaliser une gestion quantitative du risque de fissuration thermique à l'aide de l'indice obtenu par application de cette relation.

Mots-clés: Barrage Béton, Fissuration, Mesure De Température, Monitaring Auscultation Automatique, Construction, Refroidissement.

1. INTRODUCTION

Temperature in Japan ranges widely from higher than 30°C to below the freezing point. Since the land of Japan is long in the north–south direction, the country encompasses a number of climate zones from subarctic to subtropical so that temperature differs widely from region to region. Climate change has been showing a tendency to intensity in recent years, probably under the influence of global warming, and there is growing concern about the possibility of thermal cracking of concrete caused by increasingly greater changes in temperature. The temperature gradient occurring between the surface and the interior of the dam concrete, which is a factor contributing to cracking due to internal restraint, is likely to be greater than expected. It is therefore important to achieve highly reliable risk management of cracking reflecting the actual site conditions.

When analyzing the thermal cracking risk of a concrete dam, it is common practice to analyze the thermal cracking risk of a block with the largest cross section, which is likely to be most susceptible to cracking, by using techniques such as the finite element method for thermal stress analysis. At the planning stage, concrete placement is scheduled so as to prevent thermal cracking by implementing control measures such as comparing thermal cracking risks through simulations in which the time to start concrete placement is varied acceding to the season. At the construction stage, regulation of temperature measures such as cooling in summer and thermal retaining curing in winter with the aim of preventing thermal cracking of concrete.

In reality, however, cracks that need to be repaired do occur even at dam sites where efforts such as thermal cracking risk analysis and regulation of temperature measures are being made. Although such cracks are thought to be caused by a combination of various factors, this study focused on the influence of temperature changes, which are thought to have become greater in recent years, developed the risk management of thermal cracking method applicable to concrete dams and applied the newly developed method for construction management in a real dam project.

2. TEMPERATURE FLUCTUATIONS DUE TO CLIMATTE CHANGE

According to *Climate Change and Its Impact in Japan* (MEXT, JMA and MoE, March 2013), mean temperature in Japan, like global mean temperature, has been on the rise over the years in spite of small-scale fluctuations. In the long term, mean temperature in Japan has been rising at a rate of 1.15°C per

100 years (see Fig. 1). The year when record-breaking high temperature occurred in and after the 1990s.

In Japan, it is common practice to determine placing temperature for dam concrete according to atmospheric temperature and require that dam concrete be placed at temperatures not exceeding 25°C. Turning attention to the number of days with a daily minimum temperature of 25°C in each year, we notice that the number of 25°C or higher days per year was around 10 days increasing during the period from 1931 to 2012, and the increasing ratio of such days rose in and after 2000 (see Fig. 2).

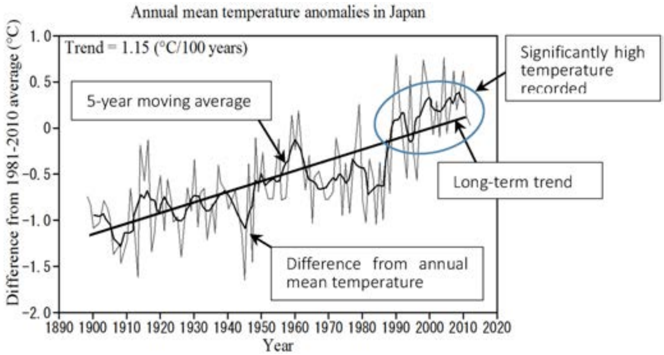


Fig. 1
Changes in Annual Mean Temperature in Japan[1]
Évolution de la température moyenne annuelle au Japon

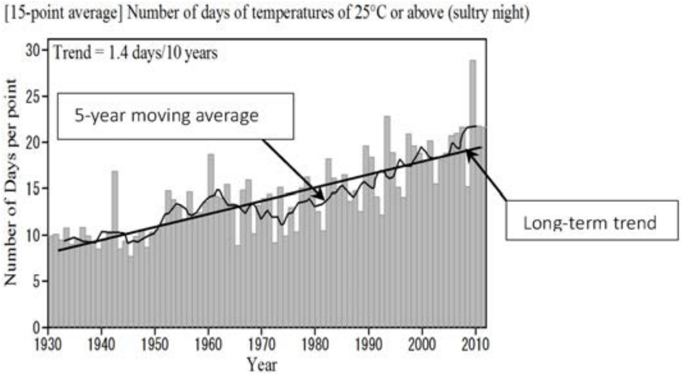


Fig. 2
Number of Days of Temperatures of 25°C or above [1]
Nombre de jours de température minimale supérieure ou égale à 25 °C

Fig. 3 shows the daily highest temperatures observed in the vicinity of a dam under construction. As shown, the daily highest temperature has risen about 3°C in the past 30 years and about 1°C in the past 10 years.

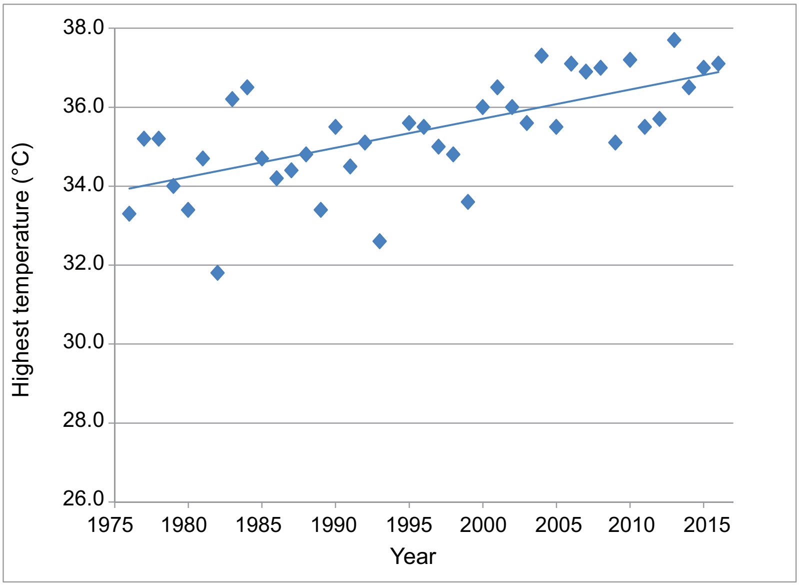


Fig. 3
Daily Highest Temperature in Vicinity of Dam under Construction
Température maximale journalière aux environs des barrages en construction

3. TEMPERATURE FLUCTUATIONS AND THEIR EFFECT ON DAM CONSTRUCTION

3.1. ACTUAL CONDITIONS OF TEMPERATURE FLUCTUATIONS INCREASING

Temperature data used for thermal stress analysis are usually determined on the basis of observation data obtained over a period of several tens of years. Temperature assumptions thus determined from recent observation results, however, tend to exceed past temperature data because of temperature rises and extreme temperature fluctuations that are thought to be attributable to climate change as mentioned earlier. Temperature values used for thermal stress analysis are usually averages of daily mean temperatures in the past several tens of years. Temperature values thus obtained, therefore, tend to show gradual changes with few extreme values. Since, however, temperature data for a particular year reflect various year-specific characteristics, fluctuations tend to be greater than those of 30-year average data as can be clearly seen from Fig. 4. Such fluctuations are thought to be due to not only statistical data processing but also climate change caused by global warming.

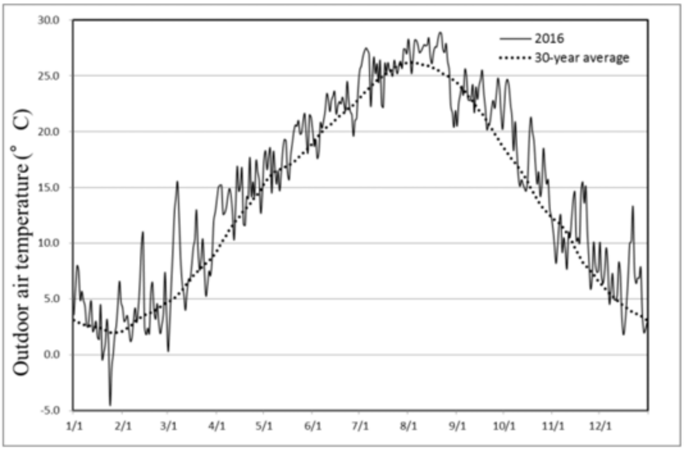


Fig. 4
Comparison of Daily Mean Temperatures in Vicinity of Dam: 30-Year Average vs. Last One Year
Comparaison des températures moyennes journalières aux envrions du barrage A : la moyenne des 30 dernières années et l'année la plus récente

3.2. THERMAL CRACKING RISK ANALYSIS AND CRACKING REGURATION SCHEME FOR DAM CONSTRUCTION

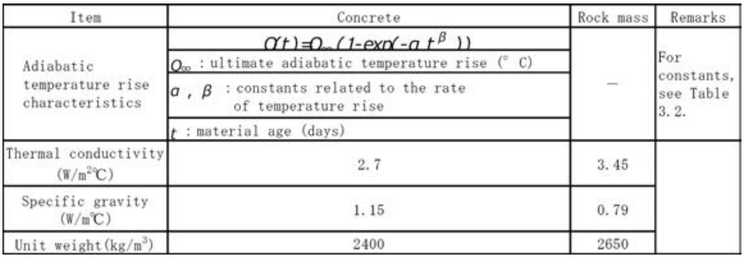
When analyzing thermal cracking risk of a concrete dam, it is common practice to focus on the block with the largest cross section block that is likely to be subject to the high risk and use such techniques as FEM (**Finite Element** Method) and thermal stress analysis. At the planning stage, concrete placement schedules are worked out by, for example, conducting simulations assuming different times to start concrete placement at different times of the year. At the construction stage, thermal cracking is controlled by taking control measures taking analysis results into consideration such as cooling in summer and thermal retaining curing in winter.

Commonly practiced thermal stress analysis and thermal crack control measures at the construction stage are described below.

3.2.1. Determination of thermal stress analysis conditions

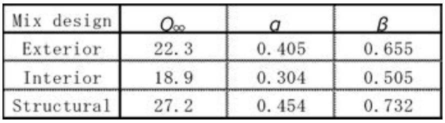
Blocks that are thought to be subject to high thermal crack risk such as a largest-cross-section block with a large opening and a rock–concrete contact zone block that is to be placed in summer are selected, and thermal stress analysis is conducted under the conditions shown in Tables 1, 2 and 3. The temperature data used for that analysis are daily average temperature data for the past several tens of years. Placing temperature is assumed to be the same as atmospheric temperature, but if it is higher than 25°C, it is assumed that cooling is carried out prior to concrete placement.

Table 1
Examples of Thermal Analysis Conditions



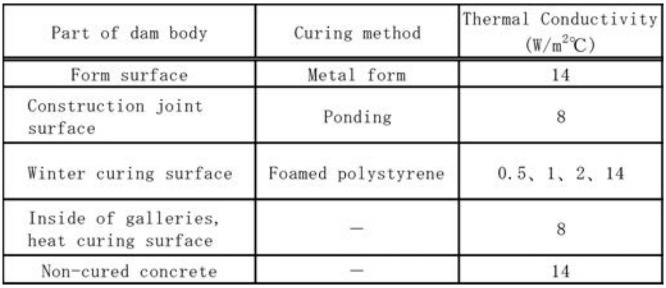
Item	Concrete	Rock mass	Remarks
Adiabatic temperature rise characteristics	$Q(t)=Q_\infty(1-\exp(-\alpha t^{\beta}))$	–	For constants, see Table 3. 2.
	Q_∞ : ultimate adiabatic temperature rise (° C)		
	α , β : constants related to the rate of temperature rise		
	t : material age (days)		
Thermal conductivity (W/m^2℃)	2. 7	3. 45	
Specific gravity (W/m℃)	1. 15	0. 79	
Unit weight (kg/m^3)	2400	2650	

Table 2
Examples of Coefficients for Formulation of Adiabatic Temperature Rise Characteristics



Mix design	Q_∞	α	β
Exterior	22. 3	0. 405	0. 655
Interior	18. 9	0. 304	0. 505
Structural	27. 2	0. 454	0. 732

Table 3
Examples of Boundary Conditions Related to Thermal Conductivity



Part of dam body	Curing method	Thermal Conductivity (W/m^2℃)
Form surface	Metal form	14
Construction joint surface	Ponding	8
Winter curing surface	Foamed polystyrene	0. 5、1、2、14
Inside of galleries, heat curing surface	–	8
Non-cured concrete	–	14

3.2.2. Thermal cracking risk indicator

It is generally said that there is a correlation between the thermal cracking index I_{cr} and the probability of occurrence of thermal cracking, $P(I_{cr})$, as shown by Eq.[1] and Fig. 5[2]. The thermal cracking index I_{cr}, therefore, is used as an indicator for thermal cracking risk.

$$P\left(Icr\right) \quad \left[\quad - exp\left\{-\left(\frac{Icr}{0.92}\right)^{-4.29}\right\}\right]\times 100 \qquad [1]$$

$$Icr \quad \frac{ft\left(te\right)}{\sigma t\left(te\right)} \leq 1.0 \qquad [2]$$

where
I_{cr}: thermal cracking index
$ft(te)$: design value of splitting tensile strength at effective age te
$\sigma t(te)$: principle tensile stress at effective age te
$P(I_{cr})$: probability of occurrence of thermal cracking

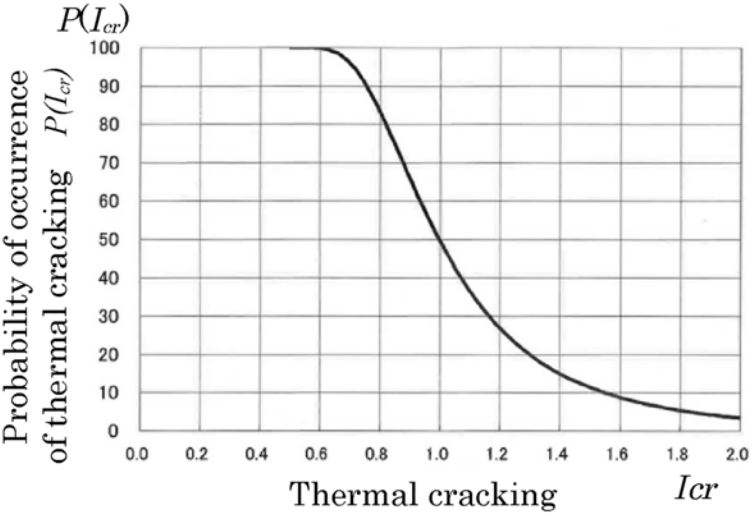
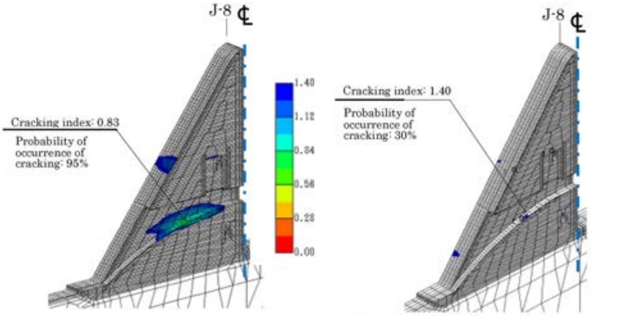


Fig. 5
Example of Relationship between Thermal Cracking Index and Probability of Occurrence of Thermal Cracking [2]
Exemple de relation entre l'indice de fissuration thermique et la probabilité de fissuration thermique

3.2.3. Example of thermal stress analysis and thermal cracking requration measures

In the example shown in Fig. 6, a region with a thermal cracking index of 0.83 occurs near the bottom of the conduit gate. It can be seen, therefore, that a cracking index of 1.40 or greater can be attained by carrying out winter heat curing (Fig. 6: upper half 1.15 → 1.49, lower half 0.83 → 1.40).

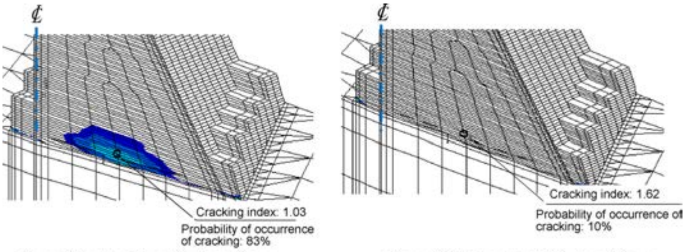


Cracking Verification Zone 1 in the Non-Curing Case

Cracking Verification Zone 1 in the Heat Curing Case

Fig. 6
Example of Thermal Cracking Index Distribution
Exemple de distribution de l'indice de fissuration thermique

In the example shown in Fig. 7, a region with a thermal cracking index of 1.03 occurs at the rock-concrete contact zone. It can be seen, therefore, that a cracking index of 1.40 or greater can be attained by carrying out pipe cooling (Fig. 7: 1.03 → 1.62)



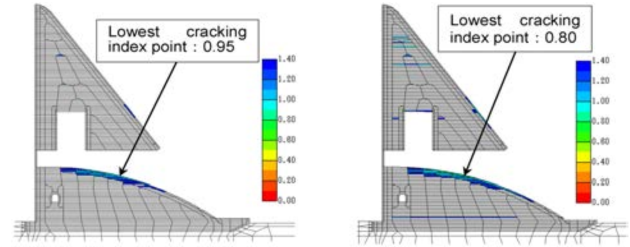
Zone 2 in the Non-Curing Case

Zone 2 in the Heat Curing Case

Fig. 7
Example of Thermal Cracking Index Distribution in Cracking Verification
Exemple de distribution de l'indice de fissuration thermique

3.3. EFFECT OF TEMPERATURE FLUCTUATIONS INCREASING ON THERMAL STRESS ANALYSIS

As shown in Fig. 4, changes in temperature experienced when dam concrete is placed are obviously greater than the changes in the 30-year daily mean temperature data used for analysis. In view of this, analysis for the purpose of verification is conducted using the values shown in Tables 1, 2 and 3 as input conditions and temperature observation data obtained during the one year before the concrete placement is started as temperature conditions. By doing so, the effect of increasing temperature fluctuations on analytical results is examined [to examine, for example, the minimum value of the thermal cracking index, the number of elements with a thermal cracking index of 1.4 (corresponding to a probability of occurrence of thermal cracking of 15%) or smaller and changes in their locations; see Fig. 8.



Temperature: Daily average of the past 30 years

The number of elements(60) with thermal cracking index of 1.4 or less

Temperature: Daily average of the one year before placement

Increasing in the number of elements(116) with thermal cracking index of 1.4 or less

Fig. 8
Thermal Cracking Index Distribution in Cracking Verification Zone 1
Distribution de l'indice de fissuration thermique dans la zone

4. THERMAL STRESS ANALYSIS METHOD AND REGURATION OF TEMPERATURE MEASURE "THE RISK MANAGEMENT OF THERMAL CRACKING"

4.1. RESPONDING TO TEMPERATURE FLUCTUATION BEYOND ASSUMED

In order to prevent thermal cracking even when responding to temperature fluctuations beyond assumed it is necessary to continually observe the construction work (e.g. atmospheric temperature, surface and internal temperature of dam concrete) so that corrective action can be taken promptly if a deviation from the management criteria has been detected. The accuracy of thermal cracking risk evaluation, therefore, is an important consideration. That is why a new management system was developed, by applying a thermal cracking risk management method focusing on three main factors concerned, namely, dam concrete observation locations, observation instruments and criteria (indicators), so that the probability of occurrence of thermal cracking can be evaluated accurately by identifying appropriate observation locations quantitatively instead of empirically and installing temperature measuring instruments at those locations.

4.2. ANALYSIS METHOD AND DETERMINATION OF DAM CONCRETE TEMPERATURE OBSERVATION POSITIONS

Dam concrete temperature observation positions to cover the entire dam structure in temperature measurement are determined in two stages. At the first stage of temperature observation location screening, a three-dimensional thermal stress analysis of the entire dam structure including the foundation bedrock is conducted to roughly determine the distribution of thermal cracking risk in the dam structure and identify high-risk blocks. At the second stage, a detailed two-dimensional thermal stress analysis is conducted of the blocks selected at the first stage to identify high-thermal-cracking-risk locations according to more specific criteria and select observation positions.

In this study, a dam under construction (hereafter referred to as Dam "A") is considered as an example.

4.2.1. Whole structure 3D model and analysis conditions

Fig. 9 shows the whole structure analysis model used. The model has a dam height of 73.0 m, a crest length of 300.0 m and a total of about 100,000 nodes, and the analysis conditions are identical to those shown in Tables 1, 2 and 3. For the compressive strength and adiabatic temperature rise characteristics, standard values were used.

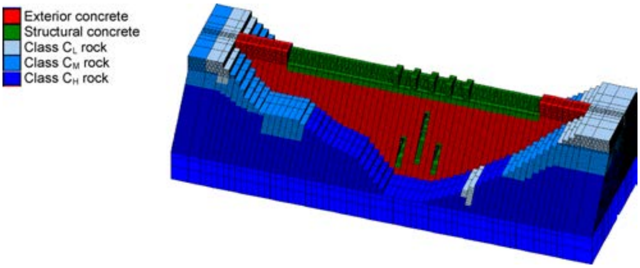


Fig. 9
3D Model of the Entire Dam
Modèle tridimensionnel de l'ensemble du barrage

4.2.2. First stage selection (extracting of high thermal cracking risk blocks)

Regions having a thermal cracking index of 1.85 (corresponding to a probability of occurrence of thermal cracking of 5%) are extracted from the thermal cracking index distribution (Fig. 10) obtained by using the thermal cracking index as a thermal cracking risk indicator on the basis of the results of the whole structure 3D thermal stress analysis.

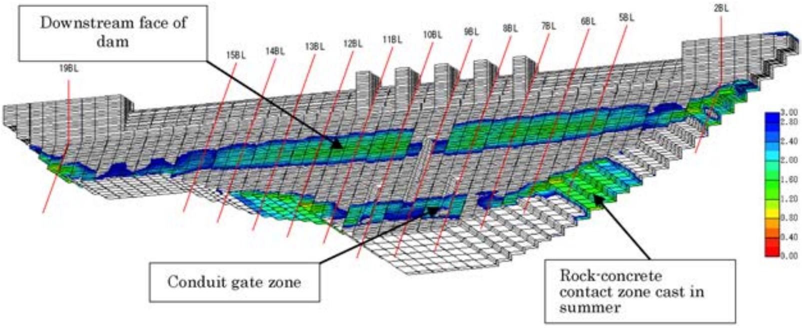
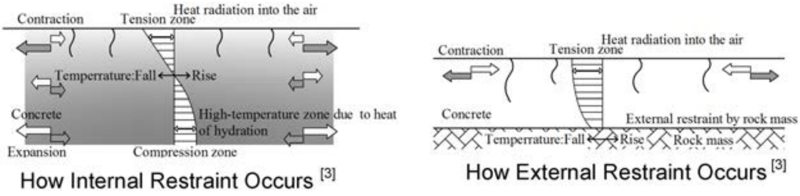


Fig. 10
Thermal Cracking Index Distribution over the Entire Dam
Distribution de l'indice de fissuration thermique dans le barrage

Mechanisms of thermal cracking can be broadly classified into two types: internal restraint and external restraint (Fig. 11). Cracking attributable to internal restraint is caused by temperature difference between the surface and the interior of the dam body concrete. Cracking attributable to external restraint results when the temperature fall of the entire dam concrete is restrained by something such as the foundation bedrock.



How Internal Restraint Occurs [3]

How External Restraint Occurs [3]

Fig. 11
How Internal Restraint Occurs [3]
Schéma du bridage

This paper deals with cracking in the conduit gate zone (BL8), which is thought to be a kind of thermal cracking resulting from internal restraint.

4.2.3. Second stage selection (screening of observation locations)

After highest thermal cracking risk blocks are extracted from the first screening stage, an analysis model is constructed as shown in Fig. 12, and a detailed two-dimensional thermal stress analysis is conducted. The analysis conditions are the same as the conditions for the whole dam structure analysis of the dam (Tables 1, 2 and 3).

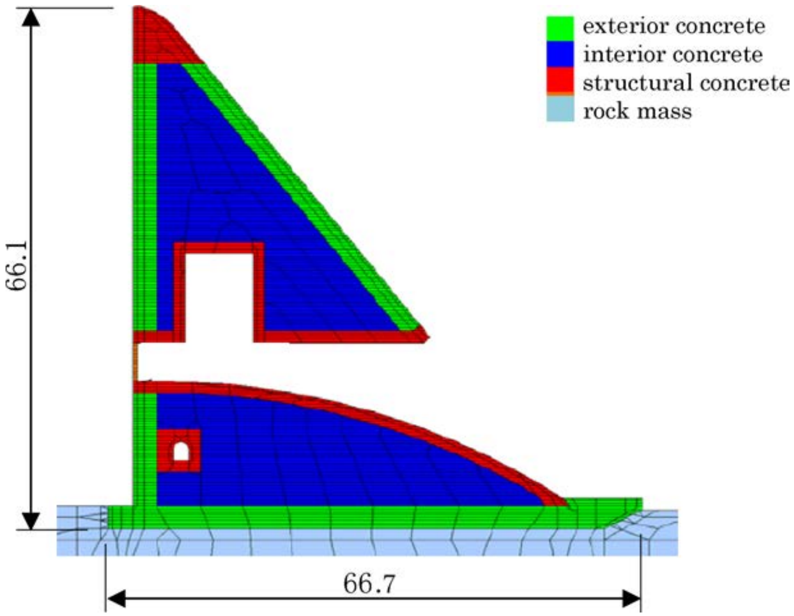


Fig. 12
Detailed Two-Dimensional Thermal Stress Analysis Model
Modèle pour l'analyse détaillée des contraintes thermiques bidimensionnelles

The results of the analysis (thermal cracking index distribution) are displayed as shown in Fig. 13. This makes it possible to set high thermal cracking risk points as temperature observation locations.

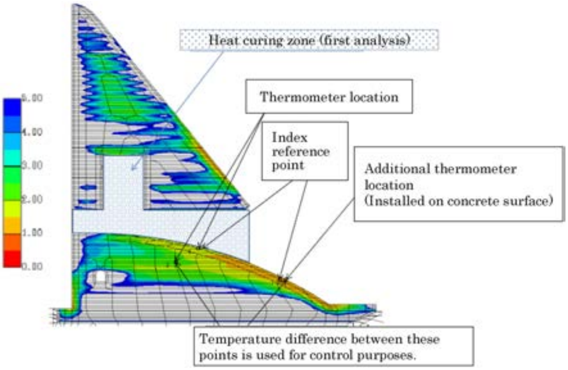
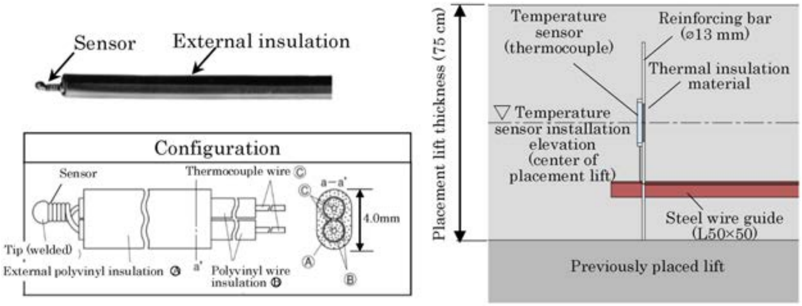


Fig. 13
Thermal Cracking Index Distribution and Instrumentation Arrangement
Distribution de l'indice de fissuration thermique et emplacement des instruments

4.3. MEASURING INSTRUMENTS

The surface and internal temperature of the dam body concrete at the specified locations are measured so that the measurements can be translated to the probability of occurrence of thermal cracking and used for management.

Thermocouples are used as temperature sensors (see Fig. 14). Because thermocouples acquire temperature information by detecting electric signals, they are simple in terms of structure, information processing and analysis, excel in measuring accuracy and are inexpensive and easy to obtain.



Temperature sensor (thermocouple)

Temperature sensor location

Fig. 14
Configuration of temperature sensor (themocouple)
Capteur de température

To install a thermocouple, its cables are placed along a steel guide installed in advance, and the surrounding concrete is carefully compacted manually so as not to cause damage. Fig. 14 illustrates the installation arrangement.

4.4. MANAGEMENT INDICATOR

The thermal cracking index and the probability of occurrence of thermal cracking are correlated as shown by Eq.[1] and Fig. 3.2. If, therefore, the thermal cracking index can be observed continuously, it should be useful as a management indicator for thermal cracking risk.

In order to observe the thermal cracking index, it is necessary to accurately determine *ft*(*te*) (design value of splitting tensile strength at effective age *te*) and t(*te*), which are the numerator (principle tensile stress at effective age *te*) and the denominator of Eq.[1]. In view of the accuracy of t(*te*) measurement, however, it is difficult to calculate the thermal cracking index from the measure value.

The author therefore turned attention to the temperature difference between the surface and the interior of the dam body concrete, which is a major factor contributing to internal restraint, and decided to estimate the thermal cracking index from temperature, which can be measured with high accuracy. The relationship between the temperature difference and the thermal cracking index is determined in advance through simulation analysis.

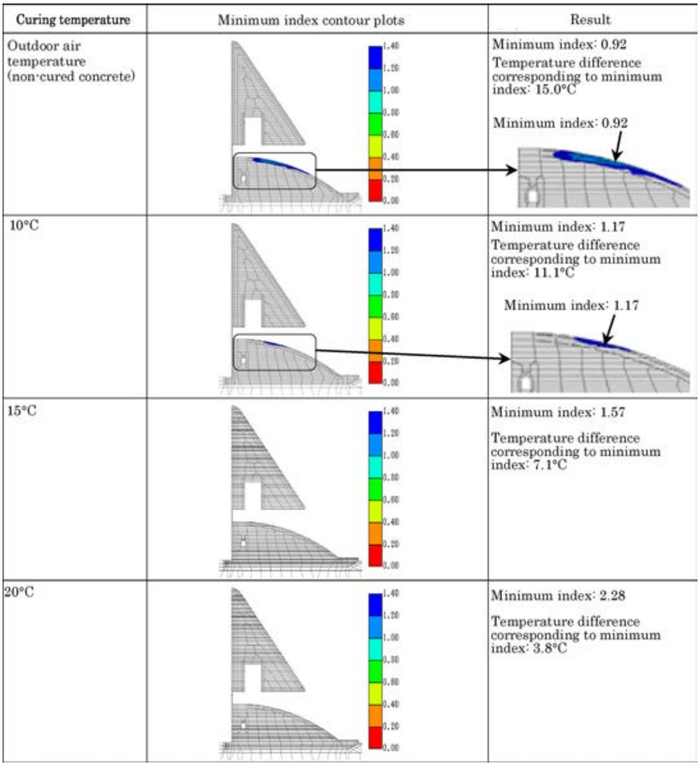
In the simulation analysis, the temperature difference between the interior and the surface of the dam body concrete is varied (for example, in the conduit gate zone of the analysis model, multiple temperature settings for winter heat curing are used; see the analysis results shown in Table 4) by using the two-dimensional thermal stress analysis model mentioned earlier, and the temperature difference between the surface and the interior of the dam body concrete and the thermal cracking index are plotted to examine their correlations (see Fig. 4.9).

Table 4 shows the analytical results for the temperature difference between the surface and the interior of the same block of dam body concrete and the thermal cracking index. The coefficient of correlation between them of higher than 0.99 (Fig. 15) indicates that the thermal cracking index can be estimated with high accuracy from the temperature difference.

4.5. THE RISK MANAGEMENT OF THERMAL CRACKING PROCEDURE

Fig. 16 shows the risk management of thermal cracking procedure described in Sections 4.1 to 4.4.

Table 4
Thermal Stress Simulation Analysis of Conduit Gate Zone under Different Curing Conditions



Curing temperature	Minimum index contour plots	Result
Outdoor air temperature (non-cured concrete)		Minimum index: 0.92 Temperature difference corresponding to minimum index: 15.0°C Minimum index: 0.92
10°C		Minimum index: 1.17 Temperature difference corresponding to minimum index: 11.1°C Minimum index: 1.17
15°C		Minimum index: 1.57 Temperature difference corresponding to minimum index: 7.1°C
20°C		Minimum index: 2.28 Temperature difference corresponding to minimum index: 3.8°C

Analysis Results

Curing temperature (°C)	Temperature difference between dam concrete surface and interior concrete A – B (°C)	Thermal cracking index
Outdoor air temperature (non-cured concrete)	15.0	0.92
10	11.1	1.17
15	7.1	1.57
20	3.8	2.28

The thermal cracking index of 1.85 (corresponding to the probability of occurrence of thermal cracking of 5%) is used as the control criterion.

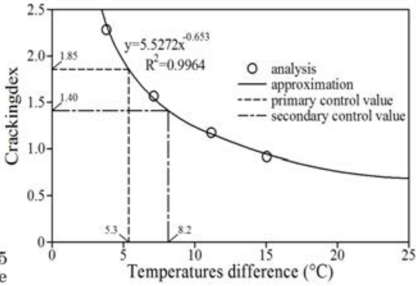


Fig. 15
Correlation between Temperature Difference and Thermal Cracking Index
Corrélation entre la différence de température et l'indice de fissuration thermique

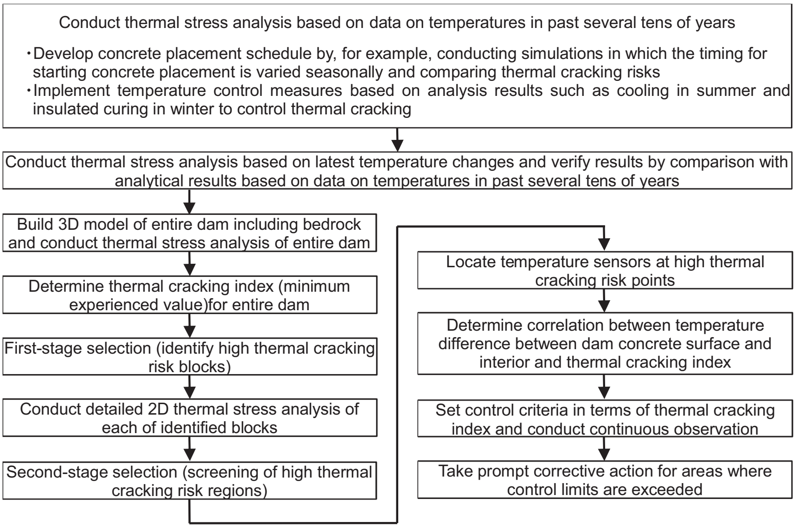


Fig. 16
Flowchart for Risk Management of Thermal Crack System
Organigramme du système de gestion du risque de fissuration thermique

5. APPLICATION OF RISK MANAGEMENT OF THERMAL CRACKING TO DAM "A"

5.1. VALUE OF THERMAL CRACKING INDEX

This section deals with the application of thermal cracking risk management to Dam A. By referring to Fig. 3.2, the thermal cracking index of 1.85 (corresponding to the probability of occurrence of thermal cracking of 5%) was adopted as the primary control criterion, and the thermal cracking index of 1.40 (corresponding to 15%) was adopted as the secondary control criterion.

5.2. MANAGEMENT BASED ON THERMAL CRACKING INDEX : HOW IT WORKS

5.2.1. Profile of Dam "A"

The thermal cracking risk management system was used for the construction of Dam "A". Dam A is a concrete gravity dam having a height of 73.0 m, a crest length of 300.0 m and a volume of 3,400,000 m^3. A general view and configuration of the dam are shown in Fig. 17 and Fig. 18.

5.2.2. *Analysis reflecting for increasing temperature fluctuations*

To compare temperature conditions, Fig. 17 and Fig. 18 show the daily mean temperature of the past 30 years and that of the one year before concrete placement. The minimum value of the thermal cracking index fell from 0.92

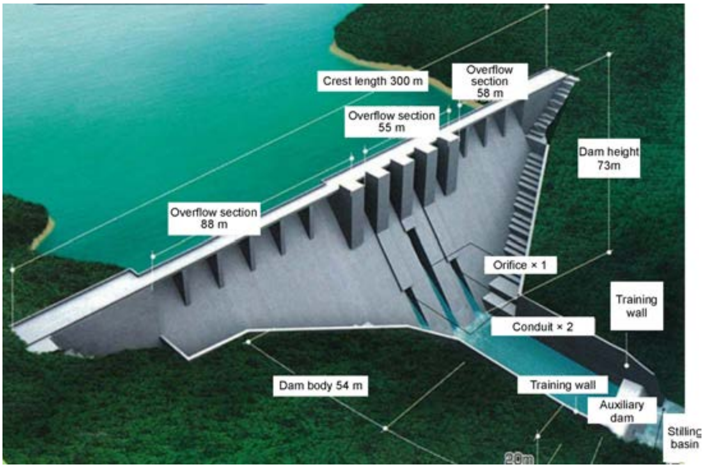


Fig. 17
General View of Dam "A"
Vue générale du barrage "A"

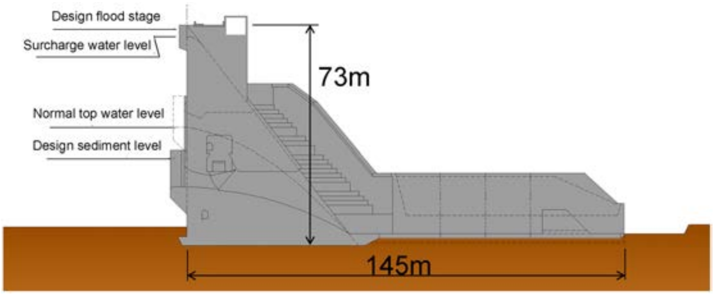


Fig. 18
Typical Cross Section of Dam "A"
Coupe type du barrage "A"

(corresponding to a probability of occurrence of thermal cracking of 60%) to 0.79 (83%). Consequently, the number of elements with a thermal cracking index less than 1.4 nearly doubled from 60 to 116, indicating the influence of increasing temperature fluctuations.

5.2.3. Determining the thermal cracking index distribution over the entire dam structure and identifying high thermal cracking risk blocks (first stage selection)

A three-dimensional model of Dam A including the bedrock was constructed, and a thermal stress analysis of the entire dam structure was conducted (Fig. 4.2). As a result of this analysis, blocks with a thermal cracking index of 1.85 (corresponding to a probability of occurrence of thermal cracking of 5%) or smaller, the downstream face of the dam, the conduit gate zone and the rock–concrete contact zone that is be placed in summer, were identified as high thermal cracking risk blocks.

5.2.4. Conducting detailed 2D thermal stress analysis of the selected blocks and thermal crack observation instruments (second stage selection)

Among the extracted high thermal cracking risk blocks, this section deals with the conduit gate zone (8BL), which is to be placed first. Fig. 4.6 shows the results of the two-dimensional thermal stress analysis. Temperature sensors were installed at locations where the temperature difference between the surface and the interior of the dam body concrete that minimizes the thermal cracking index could be observed. The location of each temperature sensor along the dam axis was at the center of each conduit gate. The temperature sensors were wired to the data logger installed in the inspection gallery to collect measurement data. The collected data were displayed on the monitor for daily management so that a warning is issued if the primary control criterion has been exceeded. When concrete was placed in a temperature sensor or wiring area, observation data was monitored continuously to make sure that wiring disconnection did not occur.

5.2.5. Correlation between temperature difference and the thermal cracking index

On the basis of the correlation between the temperature difference (between the surface and the interior of the dam body concrete) and the thermal cracking index shown in Fig. 4.9, the measured temperature difference obtained as described above was converted to the thermal cracking index so that it could be used for management.

5.2.6. Management based on thermal cracking index: how it worked

Fig. 19 shows how the thermal cracking index measurements were managed. When outdoor air temperature fell after the measurement was started, corresponding decreases in the thermal cracking index were observed. In November 2016, the thermal cracking index fell below the primary control criterion of 1.85. As a corrective measure, therefore, insulated curing of the conduit gate zone was carried out . After the curing was completed, the thermal cracking index did not fell below the primary control criterion again even when outdoor air temperature fell in winter, and thermal cracking was effectively prevented.

Fig. 19
Observation data at dam “A”
Données d’auscultation du barrage “A”

6. CONCLUSION

There is growing concern about the possible occurrence of thermal cracking of dam concrete due to greater-than-expected temperature changes which are thought to be attributable to global warming. In fact, there have been dam construction projects in which the temperature gradient between the surface and the interior of dam body concrete, a factor contributing to cracking due to internal restraint, turned out to be greater than expected at the planning stage. In order to narrow the gap between the temperature assumed at the concrete placement scheduling stage and the temperature encountered at the construction stage, a higher-accuracy risk management of thermal cracking system was developed and used in a real dam construction project.

The system observes the temperature of the surface and the interior of the dam body concrete being placed with temperature sensors embedded into the concrete being placed and manages the temperature difference by translating raw measurements into thermal cracking index data. This makes it possible to predict the trend in thermal cracking risk and take necessary corrective actions such as early insulated curing and cooling in order to further reduce cracking. In the dam construction project in which the newly developed system was put to practical use, too, the cracking risk management system proved useful in helping to prevent thermal cracking.

Risk management associated with thermal cracking due to internal restraint has been discussed thus far. Thermal cracking, however, can also be caused by external restraint, instead of internal restraint, and risk management to control such cracking is also important. The examples shown in Fig. 3.5 and Fig. 3.6 concern mainly thermal cracking due to external restraint. Since external restraint is affected by the difference between the peak temperature and the final stable temperature of dam body concrete, the next step will be to expand the applicability of thermal cracking risk management by installing temperature sensors at appropriate locations and observing temperature on a continual basis.

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