Research on influencing factors of non-stress gauge measurement on mesoscopic scale

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Abstract: Concrete stress is an important item of dam safety monitoring. The stress of dam body can be mastered and the safety degree of dam can be estimated through systematic monitoring and analysis of the stress and strain of concrete. Non-stress gauge, as well as a strain gauge group, is used to monitor the stress and strain of concrete dams. The stress-free strain of concrete can be obtained by utilizing a non-stress gauge, which is the basis for stress analysis. Results of stress-free monitoring are influenced by surrounding environments, instrument structure, and installation method. Finite element numerical simulation and meso-mechanical methods are used to study factors, such as non-uniform temperature field around the gauge, stiffness of a bucket, and aggregate state of concrete. Results show that the stiffness of bucket and non-uniform temperature field slightly influence the results of non-stress strain measurements. In addition, when the aggregate content is the same, the influence of the aggregate distribution is less. However, extra-large aggregate removal method significantly influences the monitoring results. The influence of the removal method on the stress analysis to monitor the data of the strain gauge group is evaluated using an example. Recommendations to deal with extra-large aggregate in the installation of non-stress gauges are presented.

1. Introduction

Concrete stress is an important item of dam safety monitoring. The observation results of concrete stress state are the main basis for mastering the stress state, estimating the safety degree, checking the design and construction quality of a dam body, and improving dam engineering technology. However, directly measuring the stress of dams is difficult. Carlson [1] invented the stress meter to assess stress levels. However, this instrument has limitations. For example, the instrument cannot measure tensile stress. Since there is still no good stress meter, the indirect method is widely used in every concrete dam project in the world, which determines stress by measuring strain and the conversion of strain to stress. Concrete elastic modulus, creep and temperature strain, autogenous volume strain, and other basic data must be obtained to determine stress. Elastic modulus and creep strain can be identified by laboratory testing, whereas temperature strain and autogenous volume strain are measured using a special instrument called non-stress gauge. Non-stress strain observation is the basis of observing stress in dams.

Therefore, the three main factors that affect the stress observation results include the accuracy of strain gauge measurements, the accuracy of non-stress gauge measurements, and the accuracy of elastic modulus and creep parameters of measured concrete. Various factors influence the accuracy of
strain gauge measurement, such as temperature compensation [2], length [3], mechanical properties of gauge [4], and method of installation [5]. Calderón et al. [4] argued that the two most important conditions must be met to ensure the accuracy of strain gauge measurement: (1) the good interaction between the sensor and the measured structure must be guaranteed; and (2) the presence of the sensor must not perturb the measured structure; the result indicated that the accuracy of measurements is mainly dependent on the goodness of the interaction (strain transfer) between a host material and the anchor pieces of a sensor. Several scholars conducted related research. Azenha et al. [6] studied the effect of strain gauge stiffness on measurements and determined that the effect of strain stiffness on measured values is significantly higher at the early stage of concrete than at the later stage. Torres et al. [7] examined the effect of material properties on measured values and determined that small changes in material properties can also affect measurements to a significant degree. Kesavan et al. [8] analyzed the effect of wrapper stiffness on measured values and determined that the effect of stainless steel packaging on measured values is more substantial than that of composite packaging.

Most studies focused on strain gauges and have gained a lot of knowledge, but few examined non-stress gauges. Inaccurate non-stress strain measurements cannot indicate the autogenous volume strain of concrete, and obtaining the correct stress results is difficult even if strain gauge observations are accurate [9]. Non-stress gauge is generally composed of a strain gauge and a bucket. Strain gauge is used to measure concrete strain, whereas bucket isolates concrete from external forces. The concrete in the bucket, which is free from external forces, only indicates the strain of other physical and chemical factors of concrete. Therefore, the strain of concrete in the bucket is mainly composed of temperature strain and autogenous volume strain, which includes volumetric strain caused by hydration and the hardening process of cement and possible alkali–aggregate reaction.

To ensure that a stress-free environment is the same as that of a strain gauge group, a non-stress gauge must be embedded near the strain gauge group at approximately 1 m. However, various indeterminate factors may exist in the measurement of non-stress gauge, which leads to uncertainties on whether the non-stress gauge can actually determine stress-free conditions. The main causes of uncertainty that affects the results of stress-free measurement are as follows:

1. Effect of bucket stiffness. According to Lv et al. [10], concrete in stress-free buckets may be subject to the lateral constraints of a bucket wall, thereby resulting in constrain stress. Thus, a stress-free condition is not achieved.

2. Effect of temperature field. The non-uniform temperature field [11], generally exist near a concrete surface or a water cooling pipe, may cause stress. Thus, stress-free conditions are not met if the non-stress gauge is embedded in a non-uniform temperature field, and the observed values of non-stress strain may contain temperature stress-induced strain.

3. Effect of aggregate state. When a strain gauge group of a concrete dam is buried, the large aggregate is removed from the backfill and mortar is usually added to facilitate the compaction. The mix ratio of the concrete around the strain gauge may be greatly different with that of actual dam concrete. Zhao et al. [12] noted that the effect of the removal of large aggregate on non-stress measurements must be carefully studied.

The three factors mentioned are studied using finite element numerical simulation and meso-mechanics. The effect of the removal of aggregates on non-stress strain gauge measurements was investigated. The influence of measurement error of non-stress strain gauge on the stress analysis of the monitoring data of a strain gauge group was estimated based on the research results.

2. Principle of non-stress gauge
Non-stress gauge measurements are primarily conducted to determine the actual coefficient of thermal expansion and the autogenous volume changes of dam concrete. The coefficient of thermal expansion and the autogenous volume change obtained by a non-stress gauge are used to analyze the strain of the working strain gauge group and calculate the creep stress of concrete. Monitoring the stress of concrete is mainly based on strain gauge group and non-stress gauge. Strain gauge groups measure the strain of concrete, including stress-induced strain and non-stress strain. Based on the assumption that
the total strain, stress strain, and non-stress strain in the concrete are $\varepsilon_m$, $\varepsilon$, and $\varepsilon_0$, respectively, the relationship between these types of strains can be expressed as

$$\varepsilon_m = \varepsilon + \varepsilon_0.$$  
(1)

In the in-situ observation, $\varepsilon_m$ and $\varepsilon_0$ can be directly measured, and $\varepsilon$ is calculated using Equation (1). Stress-free strain mainly includes thermal expansion strain caused by temperature changes, dry shrinkage strain caused by moisture change, and autogenous volume strain caused by cement hydration. Non-stress strain is expressed as follows:

$$\varepsilon_0 = G_t + \alpha \Delta T + \varepsilon_{\omega},$$  
(2)

where $G_t$ is autogenous volume strain caused by the physical and chemical factors of concrete, $\alpha \Delta T$ is strain attributed to temperature changes, $\alpha$ is thermal expansion coefficient of concrete, $\Delta T$ is temperature change, and $\varepsilon_{\omega}$ is strain caused by humidity. Mass concrete moisture is almost constant. Thus, strain caused by moisture inside the barrel of concrete can be disregarded.

Various types of non-stress gauges exist in different countries. Two types are generally used in the United States, as shown in Fig. 1. The first type embeds one strain meter vertically and another horizontally near the top of a concrete lift in an isolated cone of concrete, as shown in Fig. 1(a). The second type embeds a concrete pipe with length of 3 or 4 ft (0.9 or 1.2 m) and diameter of 15 in (381 mm), and a strain meter is suspended at the center of a 12 in $\times$ 24 in (305 mm $\times$ 610 mm) cylinder specimen mold of a type that permits easy stripping, as shown in Fig. 1(b). The non-stress gauge type widely used in China is similar to that in Fig. 1(b) but resembles a cone shape, as shown in Fig. 2. This type was originally obtained from Novosibirsk Hydropower Station and proposed by Adelman [13]. Although various types of non-stress gauges have been developed in different countries, these gauges are based on the same design principle.

The non-stress gauge widely used in China is made of a conical bilayer bucket in which concrete is poured in the inner cylinder and a strain gauge is embedded in the central axis. The general structure of non-stress gauge buckets is shown in Fig. 2. Taking a conical bilayer bucket for the strain gauge with length 25cm for example, the outer cylinder, inner cylinder are made of 1.2mm and 0.5mm thick metal sheet respectively, the gap between the inner and outer cylinder is around 10–30 mm and is mostly filled with foam. The inner cylinder is coated with 5 mm-thick asphalt. The concrete in the inner cylinder is not subjected to external force because of the separation of the two layers of the bucket. The concrete is integrally connected to the outer concrete only by the bung hole to maintain the same temperature and humidity as the outer concrete. Thus, the strain of the concrete in the inner cylinder is caused only by temperature, humidity, and autogenous volume changes and not by stress, i.e., the strain measured in the inner cylinder is stress-free strain.

![Fig. 1 Diagram of non-stress gauge](image)
(1 strain gauge, 2 outer cylinder [1.2 mm], 3 inner cylinder (0.5 mm), 4 foam, 5 asphalt layer (5 cm), 6 wire, 7 cable)

Fig. 2 Diagram of non-stress gauge

3. Effect of bucket stiffness

This section aims to examine whether a bucket is laterally bound to the strain of concrete. Thus, the inner concrete is examined to verify whether it is free deformation from the constraint of the bucket. The shape and size of the bucket are assumed to be the same, and only bucket stiffness changes.

The calculation model is shown in Fig. 3(a). The size of the model is set to 1.0 m × 1.0 m. The bucket is composed of double layers of metal with a foamed gap, as presented in Fig. 3(b). The size of the bucket is the same as that in Fig. 2. The calculation model is not subject to external loads but is surrounded by a normal constraint. Concrete is a homogenous material with autogenous volume strain that is assumed to increase linearly with age. The given autogenous strain curve of concrete is shown in Fig. 4. The modulus of elasticity of concrete is set to 35 GPa, and Poisson’s ratio is 0.2. The stiffness of the bucket is generally determined by the inner and outer cylinder metal sheet and the middle foam. The elastic modulus of the foam material is less than that of the metal sheet. Therefore, the foam elastic modulus is considered as 50 MPa, and the metal elastic modulus $E_s$ is set as 50, 100, 150, and 200 GPa.

Fig. 3 Computing model

Linear elastic finite element method (FEM) is used for the calculation. The measurement strain of the strain gauge was calculated by dividing the relative displacement of both ends of the strain gauge by the length of the strain gauge, as expressed by
\[ \varepsilon = \frac{L - L_0}{L_0} = \frac{(z_A + d_A) - (z_B + d_B)}{z_A - z_B} = \frac{d_A - d_B}{z_A - z_B}, \]  
\[ \text{(3)} \]

where \( \varepsilon \) is the measurement strain of the strain gauge; \( L_0 \) is the initial length of the strain gauge; \( L \) is the length of the strain gauge after calculation; \( z_A, z_B, d_A, \) and \( d_B \) are the coordinate height and displacement of the two ends of the gauge, respectively.

The calculation results of the four cases are indicated in Fig. 4. The measurement strain of the gauge of all the cases are basically equal to the given autogenous strain of concrete. The strain difference of the four cases is small. Therefore, the influence of bucket stiffness on the non-stress gauge measurement is minimal.

**Fig. 4 Results of different bucket stiffness calculations**

### 4. Effect of non-uniform temperature field

Wang et al. [11] noted that the stress-free condition is not satisfied if a non-stress gauge is in a non-uniform temperature field, and the strain measurement may contain a part of the strain caused by the stress induced by the non-uniform temperature. According to thermoelastic theory, for a 3D problem, a temperature field that does not produce a self-constrained thermal stress must satisfy

\[
\begin{align*}
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} &= 0, \quad \frac{\partial^2 T}{\partial z^2} = 0, \quad \frac{\partial^2 T}{\partial x \partial y} = 0, \\
\frac{\partial^2 T}{\partial y \partial z} &= 0, \quad \frac{\partial^2 T}{\partial z \partial x} = 0.
\end{align*}
\]  
\[ \text{(4)} \]

This set of equations is solved as follows:

\[ T = a_0 + a_1x + a_2y + a_3z, \]  
\[ \text{(5)} \]

where \( a_0 \)–\( a_1 \) are constant coefficients. Equation (5) indicates that the concrete temperature distribution must be linearly distributed to ensure that the concrete in the bucket does not produce thermal stress conditions.

This condition is not always satisfied in a complex and practical engineering structure. Non-uniform temperature fields generally exist near a concrete surface or a water cooling pipe. The temperature field near the water cooling pipe is the most uneven. In this section, the non-uniform temperature field of a cooling pipe is used as an example to study the effect of a non-uniform temperature field on non-stress gauge. The non-uniform temperature field was analyzed to determine if this temperature field disrupts the stress-free condition.

The calculation model is similar to that of the previous section, but the cooling pipe is arranged on four sides. The diameter of the cooling pipe is 20 mm, and the model is free from external constraints. The calculation model is shown in Fig. 5. The initial temperature of the concrete is 30 °C and that of the cooling water is 15 °C. The thermal boundary condition of a pipe wall is set to \( T = T_w \). The other boundary is set as an adiabatic boundary, as indicated in Fig. 5. The thermal parameters of all the materials are listed in Table 1. The mechanical parameters of all materials are the same as those in...
Section 3. The temperature field of the concrete under the action of water cooling and the thermal stress induced by the temperature field in the non-stress gauge are calculated.

The results are shown in Fig. 6. Fig. 6 (a), (b), and (c) show the temperature distribution after cooling for 3, 7, and 14 days, respectively. Fig. 6 (d), (e) and (f) indicate the stress distribution after cooling for 3, 7, and 14 days, respectively. In the early stages of cooling, the temperature gradient is large and mainly concentrated in the vicinity of the cooling pipes. As the cooling process progresses, the temperature gradient gradually develops inside the model. However, the bucket wall exhibits a strong barrier effect on temperature conduction. Thus, the temperature distribution of concrete in the bucket remains relatively uniform. In the latter stage of the cooling period, the uniformity of the temperature distribution increases. As the temperature gradient of the entire model decreases, the temperature gradient of the concrete in the bucket also reduces.

In the early cooling period, a large temperature gradient near the cooling pipe causes a large stress near the pipe, but the stress in the bucket is still zero. In the mid-cooling period, the stress near the cooling pipe begins to decrease, and the concrete in the bucket produces a certain amount of stress. However, stress remains minimal. In the latter stage of cooling, the stress of the concrete in the bucket decreases further as the overall temperature equalizes.

The results show that the non-uniform temperature field in the non-stress bucket produces a certain amount of stress. However, in actual projects, pipe cooling not only produces an excessively large temperature gradient in the concrete in the bucket because of the heat insulation of the bucket wall and the no-stress gauge is usually installed far from the cooling pipe. The produced thermal stress is not
excessively large. Thus, the effect of non-uniform temperature field on no-stress gauge measurements is minimal.

Fig. 6 Temperature and stress field at specific cooling times

5. Influence of aggregate content and distribution
Concrete is a multiphase composite material that consists of aggregate, mortar, and interface (ITZ) at the meso-scale. The results of studies on concrete meso-mechanics show that aggregate content and distribution significantly affect the properties of concrete. In the installation process of non-stress gauges, the large aggregate in the concrete is removed, which essentially changes the state of the aggregate in the concrete and alters the nature of the measured object. The influence of aggregate state changes on the coefficient of the thermal expansion of concrete and the measurement of autogenous volume strain is crucial for non-stress measurements.

5.1 Effect of random distribution of aggregates
This section aims to investigate the effect of aggregate distribution on the stress measurement of non-stress gauges under the same aggregate content and aggregate shape. Four aggregate distribution models are established, as shown in Fig. 7. The aggregate of the four models have the same number and shape, but the distribution differs. The aggregate number of one model is set to 500, and the maximum size of the aggregate is set to 80 mm. The gradation of the aggregate is fit with a full curve.

The calculation parameters of each phase of concrete are shown in Table 2. The calculation parameters of other materials are the same as those in Sections 3 and 4. For computational convenience, mortar autogenous volume strain is assumed to linearly increase with age, as indicated in Fig. 8.

The calculated results of the non-stress strain gauge are shown in Fig. 8. The calculation results show that the measured autogenous volume strains of these four models are basically the same and their differences are minimal. Thus, when the aggregate content is the same, the aggregate spatial distribution on the measurement results of the strain gauges exhibits a minimal effect.
The effect of aggregate distribution on the measurement of the coefficient of thermal expansion has been studied. All of the models are under unit uniform temperature drop, and the measured coefficients of thermal expansion of various models are calculated. The coefficients are 7.39, 7.37, 7.41, and 7.36 με/°C. These results show that the random distribution model slightly influences the coefficient of the monitoring results of thermal expansion.

![Aggregate Distribution Models](image)

**Fig. 7** Four different aggregate distribution models

![Autogenous Strain Graph](image)

**Fig. 8** Calculation results of autogenous volume strain of different aggregate distributions

| Material   | Thermal parameters | Mechanical parameters |
|------------|--------------------|-----------------------|
|            | Coefficient of thermal expansion (με/°C) | Elastic modulus (GPa) | Poisson’s ratio |
| Aggregate  | 5.0e-06            | 50                    | 0.2            |
| Mortar     | 11.0e-06           | 20                    | 0.16           |

**5.2 Effect of Aggregate Content**

The effect of the change in the aggregate content on stress-free measurements is studied in this section, including the effect on the linear expansion coefficient and the autogenous volume deformation. Six meso-scale models with aggregate contents (area fraction) of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 are established, as presented in Fig. 9. The aggregate content gradations of the six models are all set to large-sized aggregate (d = 40 to 80 mm): medium-sized aggregate (d = 20 to 40 mm): small-sized aggregate (d = 5 to 20 mm) = 3:2:2.

First, the difference of the coefficient of thermal expansion of various models is studied. In this calculation, the influencing factors of aggregate content and the changes in the elastic modulus of a mortar are considered. Due to the modulus of a hardening material develops with its age, the modulus of the mortar is set in this study as 5, 10, 15, 20, 25, 30, and 35 GPa. The modulus of the aggregate is set as 50 Gpa. The aggregate coefficient of thermal expansion is 5 με/°C. The coefficient of thermal expansion of the mortar is 11 με/°C. The other calculation parameters are the same as those indicated in Section 0.
Fig. 9 Six different aggregate content models

Table 3 Effect on coefficient of thermal expansion (μe/°C)

| Aggregate content | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0                 | 11.00 | 11.00 | 11.00 | 11.00 | 11.00 | 11.00 | 11.00 | 11.00 | 11.00 |
| 0.3               | 8.37 | 8.50 | 8.62 | 8.72 | 8.82 | 8.91 | 8.99 | 9.06 | 9.13 |
| 0.4               | 7.71 | 7.84 | 7.96 | 8.07 | 8.18 | 8.27 | 8.36 | 8.45 | 8.53 |
| 0.5               | 7.13 | 7.25 | 7.36 | 7.47 | 7.57 | 7.67 | 7.76 | 7.84 | 7.92 |
| 0.6               | 6.61 | 6.71 | 6.81 | 6.91 | 7.00 | 7.09 | 7.17 | 7.25 | 7.33 |
| 0.7               | 6.14 | 6.23 | 6.31 | 6.38 | 6.46 | 6.53 | 6.60 | 6.67 | 6.74 |
| 0.8               | 5.73 | 5.78 | 5.84 | 5.89 | 5.95 | 6.00 | 6.05 | 6.10 | 6.15 |

The calculation results are listed in Table 3. Taking the 25 Gpa mortar case as example, for these models with the aggregate contents of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, the coefficients of thermal expansion are 8.82, 8.18, 7.57, 7.00, 6.46, and 5.95 μe/°C, respectively. When the aggregate content increases by 0.1, the coefficient of thermal expansion decreases by roughly 7.0%. The non-stress gauge aggregate content substantially affects the results of the coefficient of thermal expansion measured by the non-stress gauge.

Second, the difference of the autogenous volume strain of various models is studied. The autogenous volume strain of a mortar is set as 10 μe. The results are shown in Table 4. Also taking the 25 Gpa mortar case as example, for these models with the aggregate contents of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, and the autogenous volume strain is 6.36, 5.29, 4.29, 3.33, 2.43, and 1.58 μe, respectively. When the aggregate content increases by 0.1, the autogenous volume strain decreases by around 0.8 μe, and the decrease percentage is roughly 16.8% to 34.9%. The aggregate content of concrete in the non-stress bucket significantly influences the measurement of the autogenous volume strain.
Table 4 Effect on autogenous volume strain (με)

| Aggregate content | Mortar elastic modulus/aggregate elastic modulus |
|-------------------|-----------------------------------------------|
|                   | 0.1   | 0.2   | 0.3   | 0.4   | 0.5   | 0.6   | 0.7   | 0.8   | 0.9   |
| 0                 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| 0.3               | 5.62  | 5.83  | 6.03  | 6.20  | 6.36  | 6.51  | 6.65  | 6.77  | 6.89  |
| 0.4               | 4.52  | 4.74  | 4.94  | 5.12  | 5.29  | 5.45  | 5.60  | 5.74  | 5.88  |
| 0.5               | 3.55  | 3.75  | 3.94  | 4.12  | 4.29  | 4.44  | 4.59  | 4.74  | 4.87  |
| 0.6               | 2.68  | 2.86  | 3.02  | 3.18  | 3.33  | 3.48  | 3.62  | 3.75  | 3.88  |
| 0.7               | 1.91  | 2.05  | 2.18  | 2.31  | 2.43  | 2.55  | 2.67  | 2.78  | 2.89  |
| 0.8               | 1.21  | 1.30  | 1.40  | 1.49  | 1.58  | 1.67  | 1.75  | 1.84  | 1.92  |

6. Effect on stress calculation

6.1 Preliminary estimates

The effect of large aggregate removal on the stress analysis can be preliminarily estimated based on the results in Section 5. Table 5 lists the mix proportion of three kinds of concrete in a project. The average aggregate amount is 1831 kg/m³, and the gradation ratio of aggregates is extra large (d = 80 to 150 mm): large (d = 40 to 80 mm): medium (d = 20 to 40 mm): small (d = 5 to 20 mm) = 3: 3: 2: 2. Based on the assumption that the aggregate density is 2500 kg/m³, the volume ratio of the aggregate is approximately 0.73.

Table 5 Concrete mix proportion

| Strength grade | Water-cement ratio | Fly ash content (%) | Sand rate (%) | The amount of material per cubic gauge of concrete (kg/m³) |
|----------------|--------------------|---------------------|--------------|--------------------------------------------------------|
|                |                    |                     |              | Water cement fly ash sand aggregate                      |
| C16040         | 0.41               | 35                  | 23           | 82 130 70 511 1843                                      |
| C18035         | 0.45               | 35                  | 24           | 82 118 64 538 1833                                      |
| C19030         | 0.49               | 35                  | 25           | 83 110 59 563 1816                                      |

Based on the three types of large aggregate treatments, the volume ratio of the aggregate is calculated as follows:

1) Excluding large aggregate, filled with mortar: the aggregate content becomes 1831 kg/m³ × (1-0.3) = 1281.7 kg/m³, and the volume ratio is around 1281.7 / 2500 = 0.51.
2) Excluding all concrete, filled with wet-screened concrete: the aggregate content is the same as that of the wet-screened concrete.
   The wet-screened concrete has no extra-large aggregate. Based on the assumption that one cube meter concrete excluded extra-large aggregates, the following results are obtained:
   Aggregate content is 1831 kg × (1-0.3) = 1281.7 kg.
   Concrete volume is 1 m³ - (1831 kg × 0.3) / 2500 kg/m³ = 0.65 m³.
   Thus, the aggregate content of one cube meter of wet-screened concrete is determined: 1281.7 kg/0.65 m³ = 1642.6 kg/m³.
   Thus, the volume ratio of the aggregate becomes roughly 1642.6 / 2500 = 0.66.
3) Excluding large aggregate, filled with medium and small aggregate: the aggregate content remains constant, and the volume ratio is still around 0.73.

Therefore, three treatment methods obtain three volume ratios of 0.51, 0.66, and 0.73 of aggregate. According to the results presented in Table 3 and Table 4, the coefficient of thermal expansion, autogenous volume strain reference value, and relative error can be obtained by interpolation method, as shown in Table 6.
Table 6 Interpolated result of coefficient of thermal expansion and autogenous volume strain of each removal method

| Aggregate content | coefficient of thermal expansion | autogenous volume strain |
|-------------------|----------------------------------|--------------------------|
|                   | error                            | relative error           | error | relative error |
| 0.51              | 7.51                             | 19.20%                   | 4.19  | 92.50%        |
| 0.66              | 6.67                             | 5.90%                    | 2.79  | 28.30%        |
| 0.73              | 6.31                             | 0.00%                    | 2.18  | 0.00%         |

The results in Table 6 indicate the effects of stress on the stress analysis, which are preliminary estimated. Based on the assumption that the concrete temperature decrease is 10 °C, the concrete elastic modulus is assumed to be 35 GPa, the coefficient of thermal expansion of the concrete is 10 με/°C, and the relative error of coefficient of thermal expansion is 19.2%. Thus,

\[ Δσ = EΔαΔT = 35 \text{GPa} \times 10 \muε/°C \times 19.2\% \times 10°C = 0.67 \text{MPa}. \]

Therefore, the coefficient of thermal expansion has a relative error of 19.2%, and thermal stress has an error of approximately 0.67 MPa.

Based on the assumption that the autogenous volume strain is 50 με and its relative error is 92.5%, the concrete elastic modulus is assumed to be 35 Gpa. Thus,

\[ Δσ = EΔε = 35 \text{Gpa} \times 50 \muε \times 92.5\% = 1.62 \text{MPa}. \]

Therefore, the autogenous volume strain has a relative error of around 92.5%, and the stress has an error of roughly 1.62 MPa. Preliminary assessment indicates that the aggregate content in the non-stress bucket substantially influences the stress analysis.

6.2 Project example calculation

The influence on the stress analysis is evaluated based on the calculation results of Section 5, with the actual monitoring data of a certain project as the analysis object. The dam is a concrete double-curvature arch dam with crest elevation of 610 m and maximum dam height of 285.5 m. The measuring point of the 334-m height of dam section No. 16 was taken as the analysis object. The point is embedded with a six-direction strain gauge group and a non-stress gauge. The structure of the six-direction strain gauge is shown in Fig. 10. A six-direction strain gauge consists of six strain gauges, each bound to the bracket, and the bracket frame is a tetrahedron. The location of each strain gauge of the strain gauge group is shown in Fig. 11. Based on the assumption that the strain measurement value of six strain gauges is \( e_1, e_2, e_3, e_4, e_5, \) and \( e_6, \) the strain of concrete in the Z direction can be calculated by

\[ e_z = \frac{2\sqrt{3}}{3} (-e_1 - e_2 - e_3 + 3e_4 + 3e_5 + 3e_6). \]
Fig. 10 Sectional drawing of No. 16 dam section and location of measuring points of a certain project

Fig. 11 Structure diagram of a six-direction strain gauge group
Strain measurement data and temperature data of the group of strain gauges are shown in Fig. 12. The non-stress strain gauge measurement data are indicated in Fig. 13. Before the stress analysis, the non-stress strain data must undergo regression analysis, which uses the following formula:

$$\varepsilon_0 = a_1 \Delta T + a_2 \tilde{t} + a_3 \ln(1 + \tilde{t}) + a_4 \left(1 - e^{kt}\right),$$  \hspace{1cm} (7)

where $a_1$, $a_2$, $a_3$, and $a_4$ are regression coefficients; and $\Delta T$ is the temperature difference value that is the temperature minus the initial temperature value $\Delta T = T - T_0$. $k$ is a coefficient, in the current study, $k$ is taken as $-0.01$. The $\tilde{t}$ is the age months and equals to age days / 30.

In Formula (7), $a_3 \Delta T$ can be regarded as the thermal strain, and $a_1$ is the coefficient of thermal expansion obtained by regression. The remaining $a_2 \tilde{t} + a_3 \ln(1 + \tilde{t}) + a_4 \left(1 - e^{kt}\right)$ can be considered as the autogenous volume strain of concrete.

The regression results of the non-stress strain gauge measurement data shown in Fig. 13 are $a_1 = 5.154$, $a_2 = -1.370$, $a_3 = -28.983$, and $a_4 = 315.840$. The regression results of thermal strain and the autogenous volume strain of concrete are also shown in Fig. 13.

Stress calculations can be performed based on the results of the regression analysis of the non-stress gauge data. The stress is calculated by employing the incremental method. Based on the assumption that the time is divided into a series of increments $t_1, t_2, \ldots, t_n$, the stress increment can be calculated as follows:
\[ \Delta \sigma_i = E_i (\Delta \varepsilon_i - \Delta \varepsilon_i^0 - \Delta \varepsilon_i^f), \]  
where \( \Delta \varepsilon_i \) is the strain of concrete monitoring, \( \Delta \varepsilon_i^f \) is the increment of temperature strain, \( \Delta \varepsilon_i^s \) is the increment of autogenous volume strain, \( \Delta \varepsilon_i^c \) is the increment of creep strain, and \( E_i \) is the concrete elastic modulus at time \( t_i \). The elastic modulus formula of the concrete used in the study is
\[ E(t) = E_\infty (1 - \beta_1 e^{\gamma_1 t} - \beta_2 e^{\gamma_2 t}), \]
where \( E_\infty \) is the final elastic modulus; and \( \beta_1, \gamma_1, \beta_2, \) and \( \gamma_2 \) are parameters. In this section, \( E \) is considered as \( E(t) = 44.34 (1 - 0.729 e^{-0.387 \tau} - 0.271 e^{-0.017 \tau}) \).

\( \Delta \varepsilon_i^f \) is calculated by using the following formula:
\[ \Delta \varepsilon_i^f = a(T_i - T_{i-1}), \]
where \( a \) is the coefficient of thermal expansion using the \( a_4 \) result value of regression of Equation (7).

The autogenous volume strain increment is calculated by utilizing the following formula:
\[ \Delta \varepsilon_i^s = \varepsilon_i^s - \varepsilon_i^{s-1}, \]
where \( \varepsilon_i^s \) is the autogenous volume strain of Equation (7), and
\[ \varepsilon_i^s = a_2 t + a_3 \ln(1 + t) + a_4 (1 - e^{\kappa t}). \]

The creep strain increment is calculated by the following equation:
\[ \Delta \varepsilon_i^c = \varepsilon_i^c - \varepsilon_i^{c-1}, \]
where \( \varepsilon_i^c \) is the total creep strain for time \( t_i \), which can be expressed by the following formula:
\[ \varepsilon_i^c = \sum_{j=1}^{i-1} \Delta \sigma_j C(t_i, \tau_j), \]
where \( \Delta \sigma_j \) is the stress increment of each time step, and \( C(t, \tau) \) is the unit creep of concrete, \( t \) is the time (day); and \( \tau \) is the loading age (day). The creep of the study adopts the following formula:
\[ C(t, \tau) = (A_1 - B_1 \tau^{-C_1}(1 + e^{-B_1(t-\tau)}) + (A_2 - B_2 \tau^{-C_2}(1 + e^{-B_2(t-\tau)}). \]

The calculation parameter is considered as \( A_1 = 3.656, B_1 = 5.657, C_1 = 0.219, D_1 = 9.287E-03, A_2 = 1.141E-04, B_2 = 12.676, C_2 = 2.060E-01, \) and \( D_2 = 2.269E-01. \)

Stress increment \( \Delta \sigma_i \) for each step is calculated by using Equation (8), and the stress at each step can be calculated cumulatively.

To study the effect of aggregate treatment on stress, the coefficient of thermal expansion and autogenous volume strain of concrete can be deduced. Formulas (10) and (12) are reduced to the following:
\[ \Delta \varepsilon_i^f = f_1 a(T_i - T_{i-1}), \]
\[ \varepsilon_i^s = f_2 [a_2 t + a_3 \ln(1 + t) + a_4 (1 - e^{\kappa t})]. \]

In the aforementioned two formulas, \( f_1 \) and \( f_2 \) are the reduction coefficients for the coefficients of thermal expansion and autogenous volume strain, respectively.

When the aggregate volume ratio is 0.51 (\( v = 0.51 \)), \( f_1 \) and \( f_2 \) are set as \( f_1 = (1+19.2\%) \) and \( f_2 = (1+92.5\%) \). When the aggregate volume ratio is 0.66 (\( v = 0.68 \)), \( f_1 \) and \( f_2 \) are set as \( f_1 = (1+5.8\%) \) and \( f_2 = (1+28.3\%) \). When the aggregate volume ratio is 0.73 (\( v = 0.73 \)), \( f_1 \) and \( f_2 \) are set as \( f_1 = 1.0 \) and \( f_2 = 1.0 \).

The stress calculation results of the three aggregate volume ratio cases are shown in Fig. 14. The figure shows the maximum compressive stresses are approximately 4.34 (\( v=0.73 \)), -3.71 (\( v=0.68 \)) and -2.29 (\( v=0.51 \)) MPa, respectively. Compared with the maximum compressive stresses of \( v=0.73 \) case, the relative errors of both \( v=0.68 \) and \( v=0.51 \) cases are 14.4\% and 47.2\%. The Fig. 15 shows the stress error of both \( v = 0.51 \) and \( v = 0.66 \) cases, which were calculated by subtracting the stress of \( v = 0.73 \) from the stresses of \( v = 0.51 \) and \( v = 0.66 \), respectively. The figure shows that for different extra-large aggregate removal method, the difference of the stress calculation can reach roughly 2.2 MPa. The error curves in the figure also show that, at the early stage, the error is small but increases with time. The error gradually stabilizes at the later stage.

Although the above error calculation is related to the specific stress level of measured point, the above results also reflect to a certain extent that the various treatment methods of the large concrete
aggregate in the non-stress gauge bucket variably affect the stress analysis of concrete. Therefore, the treatment of large concrete aggregate during the installation of a non-stress gauge must be examined. Third removal method is recommended for large aggregates (excluding large aggregates filled with medium and small aggregates).

![Stress results of three kinds of removal methods](image1)

**Fig. 14 Stress results of three kinds of removal methods**

![Stress difference curve](image2)

**Fig. 15 Stress difference curve of v = 0.59 and v = 0.68 from v = 0.73**

7. **Conclusions**

Non-stress strain gauge measurement is the foundation of investigating dam stress. The measurement plays an important role in strain-stress conversion calculation of concrete. It has various influencing factors, such as bucket effect, temperature field effect, and aggregate content. By using the FEM and meso-mechanical method, this study examines the effects of bucket stiffness, non-uniform temperature field, and aggregate content on measured value of the autogenous volume strain and the coefficient of thermal expansion of concrete. The conclusions are as follows:

1. The concrete in the bucket can be freely deformed, and the influence of bucket stiffness on the non-stress gauge measurement is small.

2. The non-uniform temperature field in the non-stress bucket produces a certain amount of stress, but the stress level is low because of the heat insulation in the bucket wall and the distance of the no-stress gauge from the cooling pipe. The effect of non-uniform temperature field on the non-stress gauge measurement results is minimal. In actual projects, the influence of the non-uniform temperature field on the stress-free condition of the non-stress gauge is limited.

3. When the aggregate content is the same, the influence of the aggregate distribution is less. However, the aggregate content of concrete significantly influences the measured value of the
coefficient of thermal expansion and the autogenous volume strain. When the aggregate content increases by 0.1, for the coefficient of thermal expansion, the decrease percentage can reach 7.0%, and for the autogenous volume strain, the decrease percentage can be up to 16.8% to 34.9%.

(4) Different removal method of extra-large aggregate will cause the different aggregate content of the measured concrete. This factor significantly influences the stress analysis results. Through an analysis example of the monitoring data of a practical engineering, it is revealed that the maximum stress error of the analysis results can reach approximately 2.2 MPa.

In summary, the influence of bucket stiffness and non-uniform temperature field on the measurement result is small, but the aggregate content significantly affects the measurement results. Therefore, in the process of actual instrument installation, the treatment of large aggregates inside the bucket should be controlled strictly.

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References
[1] Pirtz D, Carlson R W. (1963) Tests of strain gauges and stress gauges under simulated field conditions. Special Publication, 6: 287-308.
[2] Zeng C. (2014) Research on Influence of Temperature Value on Measured Stress of Concrete Dam. Water Resources & Power. 32(2):79-82.
[3] Rodrigues C, Inaudi D. (2010) Laboratory and Field Comparison of Long-Gauge Strain Sensing Technologies. In: European Workshop on Structural Health Monitoring:1289-1294.
[4] Calderón P A, Gisel B. (2012) Influence of mechanical and geometrical properties of embedded long-gauge strain sensors on the accuracy of strain measurement. Measurement Science & Technology, 23(6):65604-65618(15).
[5] Seo Y, Lee J H. (2012) Short- and Long-Term Evaluation of Asphalt Concrete Strain Gauge Installation Methods Applied to the KHCTR. Journal of Transportation Engineering, 138(6):690-699.
[6] Azenha M, Rui F, Ferreira D. (2009) Identification of early-age concrete temperatures and strains: Monitoring and numerical simulation. Cement & Concrete Composites, 31(6):369-378.
[7] Torres B, Payá-Zafortez I, Calderón P A, et al. (2011) Analysis of the strain transfer in a new FBG sensor for Structural Health Monitoring. Engineering Structures, 33(2):539-548.
[8] Kesavan K, Ravisankar K, Parivallal S, et al. (2010) Experimental studies on fiber optic sensors embedded in concrete. Measurement, 43(2):157-163.
[9] Wang Z, Pan L, Shen H. (2010) Abnormal Phenomenon of Non-stress Strain Gauges in Observation of High Concrete Dams. Hydropower Automation & Dam Monitoring. 34(6), 42-45.
[10] Lv Gaofeng, Wang Yujie, et al. (2015) Analysis of influence of sleeve structure on stress of non-stress meters. dam and safety 2015 (5): 73-78.
[11] Wang Tongsheng. (1978) A basic problem of non-stress gauge in concrete dam. Hydropower Automation & Dam Monitoring, 1978 (1): 66-72.
[12] Zhao Zhiren. (1984) Survey of measured values of autogenous volume change in concrete. Hydropower automation & dam monitoring, 1984 (4): 12-23.
[13] S. Y. Adelman. (1960) Field investigations of concrete hydraulic structures. Moscow, 1960:98-147.