Equivalent Inverse Analysis on Thermodynamic Parameters of Compacted Layers in RCC Dam

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Abstract. The strain softening characteristics of the roller-compacted concrete (RCC) level is a key condition in studying the bearing capacity of RCC dam. Assuming that the RCC dam unit is in the adiabatic condition, horizontal and vertical linear expansion coefficients of the RCC level are calculated. These methods were applied in practical engineering, and equivalent thermodynamic parameters can be obtained by taking the weighted squared residuals between numerical values and monitoring data as the optimization objective function in parameter inverse analysis. And the difference of the Poisson ratio and the elastic modulus, the hampering of the ontology on the layer could be reflected accurately.

1. Introduction
The construction process and the change in dam temperature have significant influence on the temperature stress field for high roller-compacted concrete dam (RCCD). Because every compacted layer’s placement time is different, the layer and the ontology own different mechanical characteristics in RCCD. Furthermore, the layer increases the particularity and complexity of the RCCD structure and becomes the main channel of dam seepage, which could weaken dam stability and alter dam stress and seepage behaviour negatively [1–2]. RCCD owns several compacted layers with multilayer structure characteristics. When the structure is divided into several units to calculate the compacted layer in the construction simulation, the workload is too heavy to achieve in actual finite element calculation [3–4]. At the initial stage of concrete placement, temperature and stress gradients in different layers vary greatly in the vertical direction. In view of the vertical and horizontal strain increments of RCCD under temperature changes, the horizontal and vertical expansions are usually different considering linear expansion coefficients of the layer and the ontology [5–6].

At present, calculating the temperature stress of RCCD with hundreds of layers during the construction and operation periods is difficult. Therefore, the uncertainty associated with these parameters should be considered. The work presented in this paper focuses on the composite structure equivalent parameters of RCCD to comprehensively reflect the temperature strain of the layer and the ontology caused by their different thermodynamic parameters without changing the temperature strain increment calculation condition. Furthermore, the equivalent inverse analysis of thermodynamic parameters will be applied to Jin’anqiao RCC gravity dam in China.
2. Equivalent solution of linear expansion coefficients
RCCD can be regarded as a plurality of compacted layers divided into the ontology, the layer and the transition. According to practical engineering, the layer thickness is much smaller than the ontology, as shown in figure 1. In the compacted layer, the elastic modulus is $E_a$, Poisson’s ratio is $\mu_a$, linear expansion coefficient is $\alpha_a$, specific heat is $C_a$, density is $\rho_a$, volume is $V_a$, and slice thickness is $b_a$. In the ontology, the elastic modulus is $E_c$, Poisson’s ratio is $\mu_c$, linear expansion coefficient is $\alpha_c$, specific heat is $C_c$, density is $\rho_c$, volume is $V_c$, and thickness is $b_c$. The thickness of the compacted concrete layer unit is $B = b_a + b_c$, where the unit length is taken in the $x$ and $y$ directions.

![Figure 1. Compacted concrete unit composed of the ontology and the layer.](image)

Taking the deformation harmony of the ontology and the layer as the premise, equivalent parameters of the composite layer are determined when continuous gradual changes of mechanical parameters and equivalent orthotropic zones of the ontology and the layer are considered. In RCCD, a certain attenuation creep can be produced by a high water head, and the instantaneous elastic recovery with retained permanent residual strain occurs during unloading. Therefore, the improved rheologic model is used to simulate the viscoelastoplastic rheological law of the RCC layer [7–8]. And the normal serial model and the tangential parallel model of the RCC level can be established assuming that the effect zones of the RCC layer are orthotropic.

Assuming that the RCCD unit is under the adiabatic condition, except that two surfaces perpendicular to the axis own the heat exchange with the external, the ontology and the layer own the same temperature changes with no other external force. And the heat energy change in the unit is equal to that outside according to the energy conservation principle and the heat conduction equation.

2.1. Vertical linear expansion coefficient
Let $\alpha_v$ be the vertical equivalent linear expansion coefficient of the RCC unit, $\rho_v$ the equivalent density, $\Delta T_v$ the equivalent temperature change (temperature rise or drop), and $C_v$ the equivalent heat ratio. Under above assumptions, the heat generated by the temperature change in the RCC unit is equal to the changes in inside and outside energies. The energy generated by the temperature change in the compacted concrete unit is equal to the sum of the external heat flowing into the unit and the internal hydration heat.

$$C_a \rho_a \Delta T_a V_a + C_c \rho_c \Delta T_c V_c = C_v \rho_v \Delta T_v V_v$$

(1)

According to thermodynamics,

$$C_v \rho_v V_v + C_c \rho_c V_c = C_v (\rho_a V_a + \rho_c V_c)$$

(2)

The geometric equation in the vertical direction is $\Delta l_a + \Delta l_c = \Delta l$. The physical geometric equation is $\Delta l_a = \Delta T_a \Delta l_a$, $\Delta l_c = \Delta T_c \Delta l_c$. Then, the following equation can be obtained
\[ \Delta T_a \alpha_a b_a + \Delta T_c \alpha_c (B - b_c) = \Delta T \alpha_e B \]  

(3)

In addition, \( \rho_v = (\rho_a V_a + \rho_c V_c)/(V_a + V_c) \), through the simultaneous solution of above equations, equivalent vertical thermodynamic parameters of the compacted concrete unit are

\[ \Delta T_v = \frac{C_v \rho_v \Delta T V_a + C_c \rho_c \Delta T V_c}{C_v \rho V_a + C_c \rho V_c} \]  

(4)

\[ C_v = \frac{C_v \rho V_a + C_c \rho V_c}{\rho_a V_a + \rho_c V_c} \]  

(5)

\[ \alpha_v = \frac{\Delta T_a \alpha_a b_a + \Delta T_c \alpha_c (B - b_c)}{\Delta T B} \]  

(6)

2.2. Horizontal linear expansion coefficient

Under the changes in dam temperature, horizontal expansions of the ontology and the layer are different because of their different expansion coefficients. Assuming that the layer expansion coefficient is \( \alpha_a \), the temperature change is \( \Delta T_a \), the ontology expansion coefficient is \( \alpha_c \), the temperature change is \( \Delta T_c \), the horizontal strain produced by the ontology is \( \varepsilon_c = \Delta T \alpha_c \) and the strain produced by the layer is \( \varepsilon_a = \Delta T_a \alpha_a \). The junction bonded firmly to the ontology and the layer according to the deformation compatibility, \( \Delta l_a = \Delta l_c \). However, the deformation of the free expansion \( \Delta T \alpha_a \) and \( \Delta T_a \alpha_a \) are not necessarily equal, implying the existence of a certain amount of strain increment in the combination of the ontology and the layer (referred to the weak surface commonly). Temperature changes produce micro stress in the weakness plane. Therefore, the horizontal strain increment cannot be simply described as \( a \Delta T \), which means that the temperature strain and variation are nonlinear in the compacted level junction.

The equivalent horizontal linear expansion coefficient of RCC unit \( \alpha_a \) will be explored to reflect the temperature effect of the ontology and the layer. Assuming that the equivalent density is \( \rho_v \), the equivalent temperature change is \( \Delta T_v \), the equivalent specific heat is \( C_v \), the equivalent horizontal elasticity modulus is \( E_v \), the ontology temperature change is \( \Delta T_c \) and the layer temperature change is \( \Delta T_a \). The ontology and the layer undergo uniform temperature changes. The compacted concrete unit possesses the following characteristics that are affected only by temperature load.

Static equilibrium equation is

\[ \alpha_v = \frac{\Delta T_c \alpha_c b_a + \Delta T_a \alpha_c (B - b_c)}{\Delta T B} \]  

(7)

Given the thinness of the RCC layer, the geometry equation is approximately \( \varepsilon_{as} = \varepsilon_{cs} = \varepsilon_c \). The physical equation is \( \varepsilon_{cs} = \frac{\sigma_{cs}}{E_c} + \alpha_c \Delta T_c \) and \( \varepsilon_{as} = \frac{\sigma_{as}}{E_a} + \alpha_a \Delta T_a \). Through the simultaneous solution,

\[ \sigma_{cs} = \frac{b_c E_c E_a (\alpha_c \Delta T_a - \alpha_c \Delta T_c)}{E_a b_a + E_c (B - b_c)} \]  

(8)

\[ \sigma_{as} = \frac{(B - b_a) E_a E_c (\alpha_c \Delta T_c - \alpha_a \Delta T_a)}{E_a b_a + E_c (B - b_c)} \]  

(9)

By substituting the microscopic stress into the physical equation, the horizontal equivalent linear expansion coefficient is


\[
\varepsilon_i = \frac{b_a E_a (\alpha_a \triangle T_a - \alpha_c \triangle T_i)}{E_a b_a + E_c (B - b_a)} + \alpha_i \triangle T_i = \frac{(B - b_a) E_c (\alpha_c \triangle T_a - \alpha_a \triangle T_i)}{E_a b_a + E_c (B - b_a)} + \alpha_a \triangle T_a = \alpha_e \triangle T_i
\]

Thus,

\[
\alpha_i = \frac{\alpha_e \triangle T_i}{\triangle T_i} = \frac{(B - b_a) E_c (\alpha_c \triangle T_a - \alpha_a \triangle T_i)}{E_a b_a + E_c (B - b_a)} + \alpha_a \triangle T_a = \frac{b_a E_a (\alpha_a \triangle T_a - \alpha_a \triangle T_i)}{E_a b_a + E_c (B - b_a)} + \alpha_e \triangle T_i
\]

where \( \triangle T_i = (C_i \rho_a \triangle T V_a + C_i \rho V) / (C_i \rho V_a + C_i \rho V) \).

When temperature changes between the ontology and the layer are greater or lesser, \( \Delta T_e \approx \Delta T_a \).

Moreover, it can be approximated that

\[
\alpha_i = \frac{(B - b_a) E_c (\alpha_a - \alpha_c)}{E_a b_a + E_c (B - b_a)} + \alpha_a = \frac{b_a E_a (\alpha_a - \alpha_c)}{E_a b_a + E_c (B - b_a)} + \alpha_c
\]

3. Case study

The Jin'anqiao RCC gravity dam with “gold around silver” mode is presented as an example, with a dam crest elevation of 1424 m and a maximum dam height of 160 m. Abnormal concrete is used in the upstream and downstream surfaces as the waterproof layer. Pouring in the powerhouse dam began in April 11, 2007 and was completed in March 23, 2009. The dam foundation height and crest elevation are 1268.0 m and 1375.0 m, respectively. The average concrete pouring temperature was at 16.1 °C through cooling water pipes with an average water temperature 12.1 °C. Figure 2 shows the following material partition: above the 1366 m section elevation is the normal concrete layer, the base has four graded layers of normal concrete, the upstream side has three graded RCC, and the remaining has two graded RCC.

The dam finite element model is shown in figure 3. The RCC level thickness is \( B=30 \) cm and the layer thickness is \( b_a=2 \) cm. The linear expansion coefficient of the ontology is \( \alpha_a = 9.8 \times 10^{-6} \text{C}^{-1} \), the elastic modulus of the ontology is \( E_a = 2.8 \times 10^4 \text{GPa} \), the density of the ontology is \( \rho_a = 2.4 \times 10^3 \text{kg/m}^3 \), and the specific heat capacity of the ontology is \( C_a = 0.75 \text{kJ/kg}^\circ \text{C} \). The linear expansion coefficient of the layer is \( \alpha_c = 8.2 \times 10^{-6} \text{C}^{-1} \), the elastic modulus of the layer is \( E_a = 1.2 \times 10^4 \text{GPa} \), the density of the layer is \( \rho_c = 1.9 \times 10^3 \text{kg/m}^3 \), and the specific heat capacity of the layer is \( C_c = 1.8 \text{kJ/kg}^\circ \text{C} \).

Considering water inpouring and concrete cooling during the construction period, the numerical calculation is performed to simulate dam pouring process to 3138.0 m, 1360.0 m, and 1422.5 m, water inpouring to 1398.0 m and 1417.0 m, and running for 2 and 3 years. The dam temperature fields of above conditions are shown in figures 4 and 5. On the basis, the equivalent inverse analysis of the thermodynamic parameters can be obtained.
Combining dam plumbline and thermometer monitoring data, inversion results of the thermodynamic parameters of RCCD are shown in Table 1. Equivalent thermodynamic parameters are: RCC unit comprehensive heat $C=0.806$ kJ/kg °C, vertical equivalent linear expansion coefficient $\alpha_v = 9.819 \times 10^{-6}$°C$^{-1}$, and transverse equivalent linear expansion coefficient $\alpha_w = 9.752 \times 10^{-6}$°C$^{-1}$.

| RCC  | Elastic modulus (GPa) | Linear expansion coefficient (°C$^{-1}$) | Specific heat capacity (kJ/kg °C) |
|------|------------------------|------------------------------------------|----------------------------------|
| Ontology | 2.8\times 10^4     | 9.8\times 10^{-6}                        | 0.75                             |
| Layer   | 1.2\times 10^4       | 8.2\times 10^{-6}                        | 1.8                              |

Then, the model is adjusted according to these parameters to calculate the vertical stress in dam pouring and water inpouring stages, as shown in figures 6 and 7.

Assuming that the layer temperature increase is 12 °C and the ontology is 15 °C, the transverse micro stress generated $\sigma_w = -4.04 \times 10^{3}$MPa in the ontology and $\sigma_w = -5.66 \times 10^{1}$MPa in the layer under temperature changes. If the microscopic stress influence is neglected, the ontology strain is $1.47 \times 10^{-4}$ and the layer strain is $9.84 \times 10^{-5}$. If the micro stress effect is considered, the comprehensive strain of RCC is $1.43 \times 10^{-4}$ under the temperature changes mentioned above.
According to the calculation results, the vertical linear expansion coefficient is slightly less than the horizontal expansion coefficient because of certain constraints of the ontology to the layer in the RCC transverse deformation. At the same time, considering the difference between the Poisson ratio and elastic modulus, the constraint of the ontology on the layer is reflected when equivalent parameters are used during the calculation. Moreover, the micro stress can be generated at the junction of the ontology and the layer under temperature loads, whose effect on the transverse strain of the RCC level is relatively large, which could explain the weakening of the thin layer in RCC dam, too.

4. Conclusions
The normal serial and tangential parallel models of the linear equivalent expansion coefficient are established according to the energy conservation principle and the heat conduction equation. Differences in the ontology and the layer and their interactions are reflected in the thermodynamic parameter inverse results of practical engineering. Moreover, macro stress is generated in the RCC layer by the temperature load results in the weakening of the thin layer in RCCD.

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